4.5 NEUTRINO BEAM MONITORING (WBS 1.1.5)

4.5.1 Introduction

The neutrino beam monitoring system enables the users to verify the quality of the beam being delivered to the experiment(s). The monitors measure the flux and spatial distribution of:

- secondary hadrons (and non-interacting primary protons) measured by the "Hadron Monitor", located just upstream of the hadron absorber,
- muons, which are directly associated with the production of neutrinos, measured by the "Muon Monitors," located downstream of the hadron absorber and at various locations within the dolomite muon shield.

The locations of the monitors are shown in **Figure 4.5-1**. The monitors' intensity measurements are normalized to the incoming proton intensity while the measured spatial distributions of particles are compared to nominal spatial distributions recorded as the beam is being commissioned.

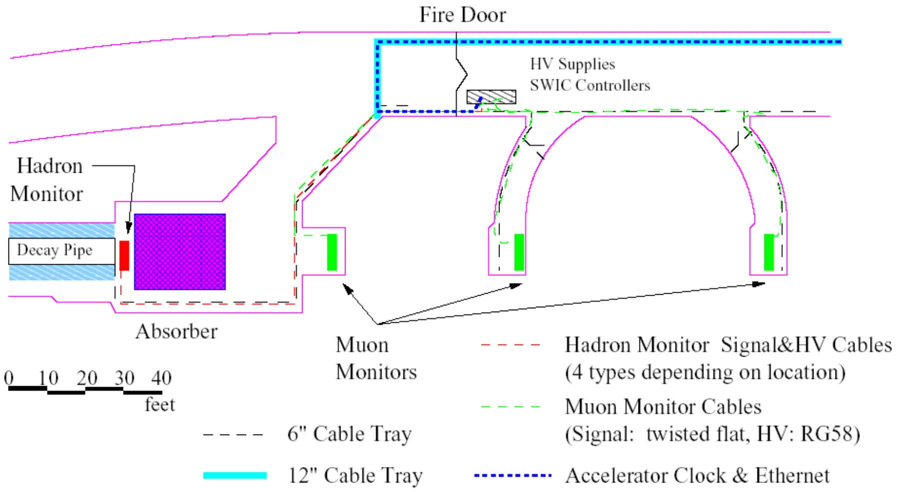

Figure 4.5-1 Plan view of the monitoring system: the hadron monitor is upstream of the absorber stack and the muon monitors are in the absorber enclosure and within the dolomite shielding

Both the Muon and Hadron Monitors are used to commission the NuMI beamline. In addition, during normal neutrino beam running for the MINOS experiment, the monitors serve as accurate neutrino rate monitors. Finally, during periodic specialized runs the monitors serve to re-check the neutrino beam direction toward Soudan.

4.5.2 The Hadron Monitor

4.5.2.1 System Function

The hadron monitor is designed primarily for commissioning the NuMI beamline. Specifically, it will align the proton beam prior to the installation of the horns and target in the target hall. The proton beam alignment is set within the quantitative limits described in Section 4.6 (about 50μrad).[1] **Figure 4.5-2** shows the signal expected in the Hadron Monitor during commissioning.

During normal neutrino beam operations with the horns and target in place, the hadron monitor tracks the proton spot, and can also monitor the integrity of the NuMI target. However, these latter functions are redundant with other instrumentation, such as the multiwires and BPM's or the muon monitors, so are not essential. If the Hadron Monitor should fail after extended running, it will have been highly radioactivated by the beam. As a result, the hadron monitor will only be replaced if a long shutdown permits. The likelihood or urgency of the replacement requirement will depend on operational experience with the NuMI beam. **Figure 4.5-2** shows the expected signal during normal beam operations: the magnitude of particle scattering in the target serves as a check of the full target integrity.

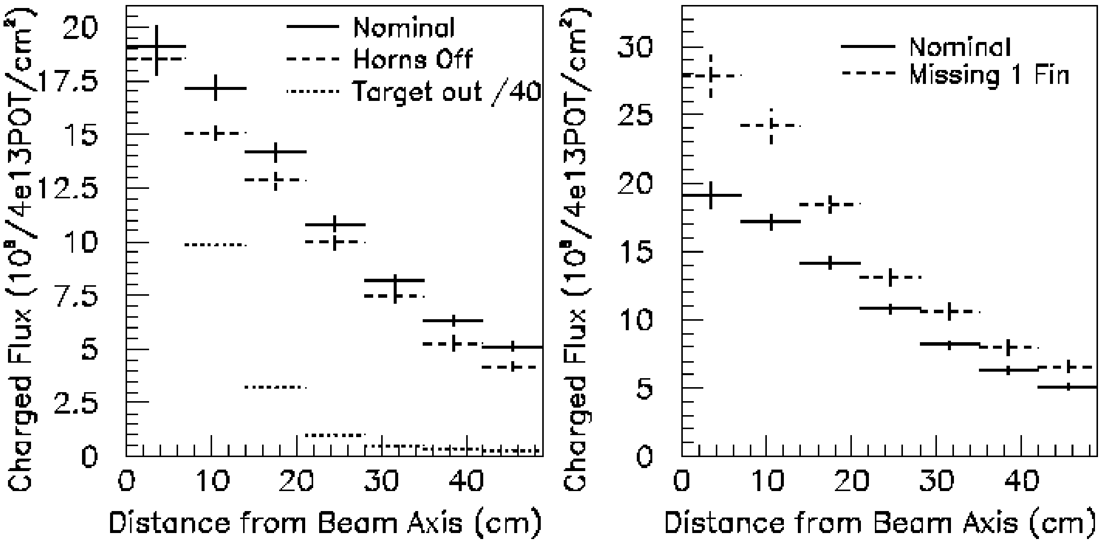

Figure 4.5-2 (left) Charged particle fluxes at the hadron monitor as a function of the distance from the center of the beamline. Fluxes for running with the target in (nominal) and out are shown. (right) Effect on Hadron Monitor signals if 15 cm of the 1 m target breaks off.

---

[1] Smart, W. NuMI-L-221, 31 Oct. 1996

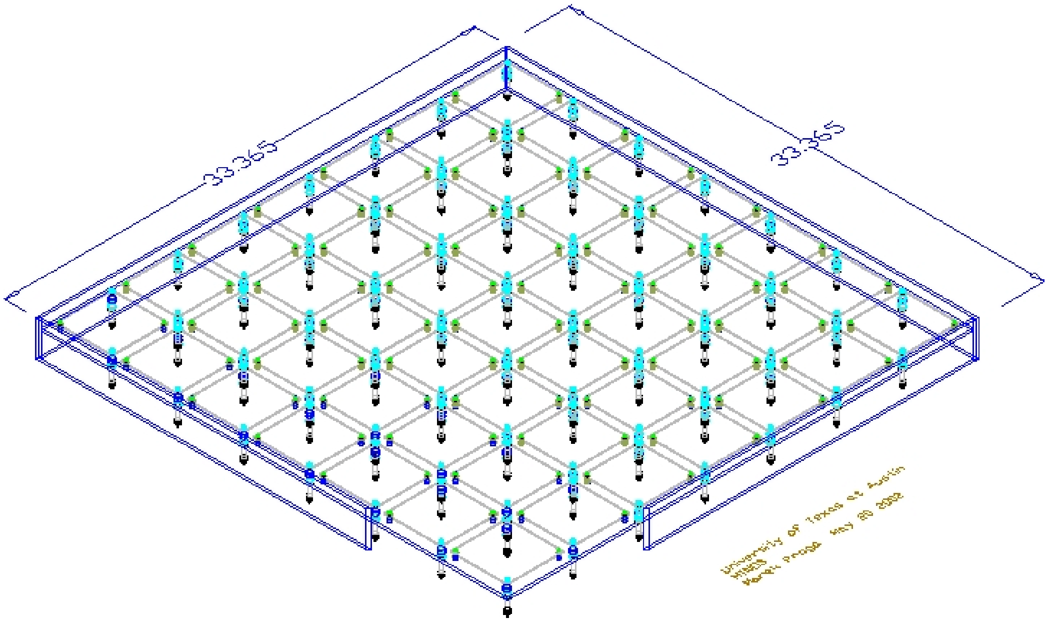

Figure 4.5-3 Schematic layout of the Hadron Monitor gas vessel and 7x7 array of ion chambers.

4.5.2.2 System Description

The hadron monitor is a 1x1 m^2 Aluminum gas vessel encasing an array of parallel plate ionization chambers (see **Figure4.5-3**). The chambers are mounted to the rear wall of the gas vessel on electrical feedthroughs. A thin front window of 0.010" Aluminum is mounted to the box. It is welded to a flange that compresses an Aluminum wire gasket to the box. It is not anticipated to open this lid for chamber repair after the hadron monitor has been in the beam. The vessel is 34” x 34”. Each 4”x4” ion chamber plate is separated from its neighbor by 0.5”.

Figure4.5-4 shows the drawings for the ceramic plates of the parallel plate ion chambers. The wafers are 1mm 96% pure Aluminum oxide, with Pt-Ag alloy electrodes.[2] Electrical connections to the grounded guard ring, the sense pad, and the HV plane are made through the corner holes to the rear of the board, where solder connections are made. Deviations from flatness, based on a preliminary order of 20 boards, are less than 0.003" across the 4" plate. The plates are separated by 1mm, the gap defined by precision ceramic washers.

---

[2] Cer-Tek, Incorporated, El Paso, Texas.

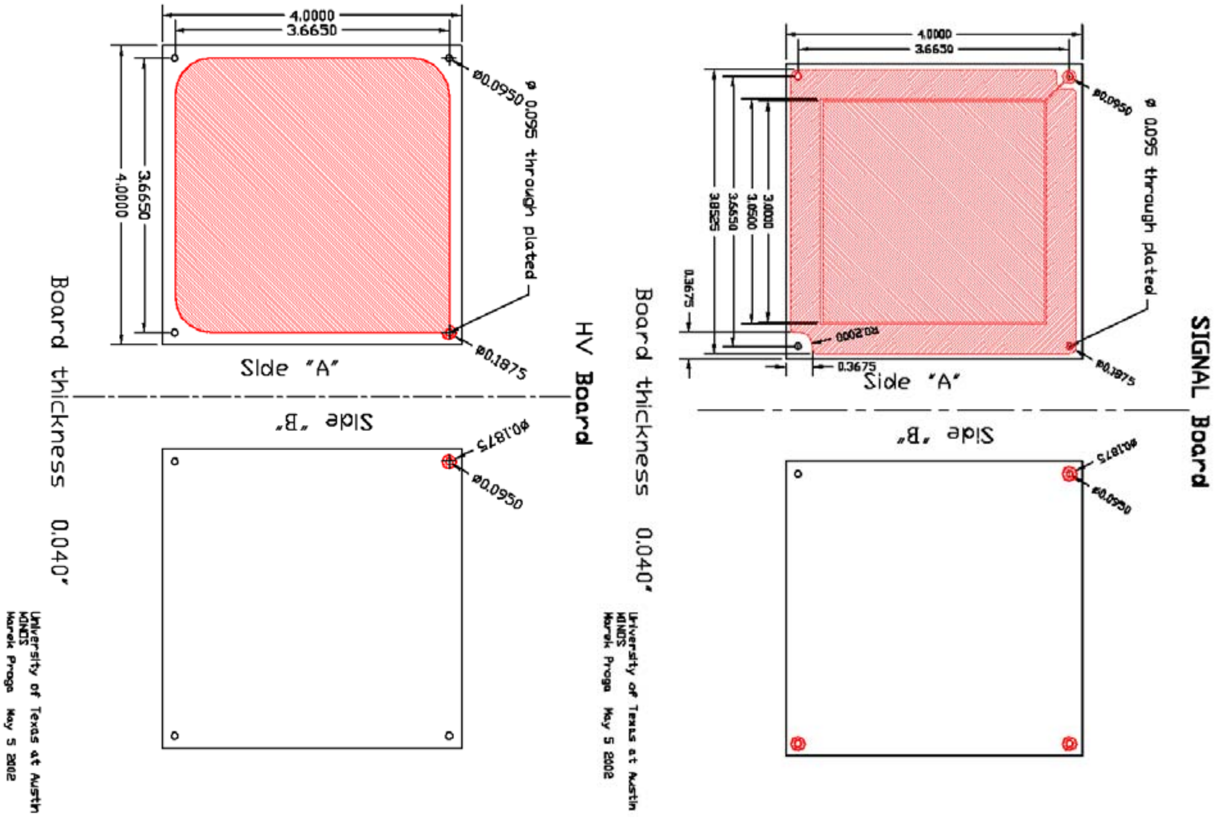

Figure 4.5-4 Design of the metalized ceramic pads that make up one parallel plate ion chamber inside the hadron monitor: (above) HV plan (below) signal plane with guard ring.

Figure 4.5-5 shows how the parallel plate chambers are mounted on the rear wall. Two commercially available HV feedthroughs (rated to 10 kV in vacuum) penetrate the rear Aluminum wall of the hadron monitor box.[3] The feedthroughs consist of a central stainless pin Kovar-sealed to a ceramic insulator. The ion chamber plates are soldered directly to the feedthrough pins at the corners, thus providing both the mechanical support of the chamber and the electrical contacts. An explosion-bonded Al-Stainless piece is used to make the weldments between the feedthroughs and aluminum box.

The cables delivering HV and bringing signals out of the hadron monitor consist of two pieces. Immediately behind the monitor, where the rad levels are highest, the coax cables are made of aluminum central and outer conductors with ceramic tubing as the dielectric. All the parts are made of commercially available wire or tubing. At the edge of the monitor, these

---

[3] Made by Insulator Seal, Incorporated, Hayward, CA.

cables are attached to kapton-insulated coax cable.[4] The kapton cable brings the lines out to the edge of the absorber shielding when the hadron monitor is in place, where a transition box will convert this to standard twist-n-flat.

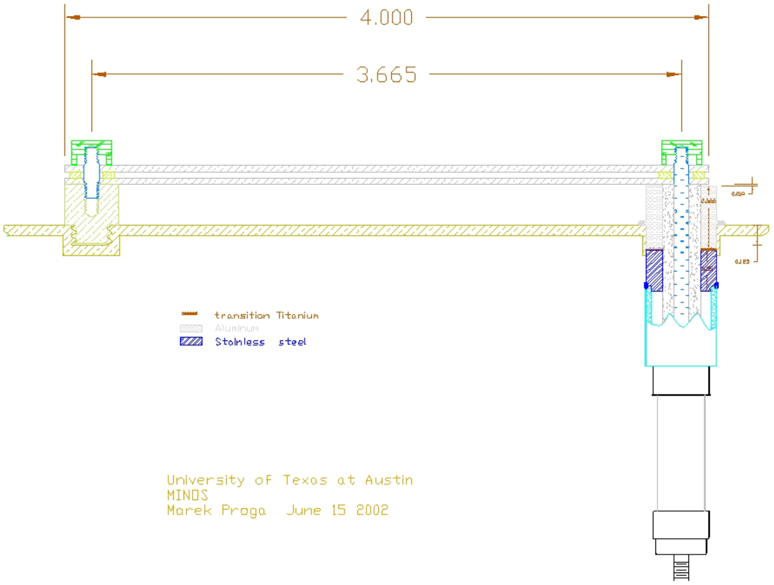

Figure 4.5-5: The mounting and signal feedthrough for a single ion chamber. Ceramic-insulated feedthroughs both support the chamber and deliver HV/signal through the gas vessel wall. The HV and signal feedthroughs are at opposite diagonal corners of the plates, and the other two corners are simple Aluminum standoffs.

4.5.2.3 Fluences, Doses

The hadron monitor is exposed to up to 10^9 charged particles/cm^2/spill during beam operation, consisting predominantly of 120 GeV protons which fail to react in the target. In addition, the monitor sees 2 x 10^9 neutrons/cm^2/spill, largely as a result of splashback from the hadron absorber located 80 cm downstream of the monitor. The particle fluences result in 1.3GRads/year at the monitor center and 1.0Grad/yr at its edge

It is estimated that the total mass of the Hadron Monitor, including all cables that must be disposed of with the detector in the event of failure, is of order 55 pounds. Of this mass, 47lbs. is Aluminum or Aluminum oxide so will have short half life after irradiation by the beam. The remaining 5 pounds is predominantly stainless steel used to make the vacuum connections, and will account for 90% of the residual activation. The residual activation is approximately 50Rem/hr on contact after 1 year of irradiation and 1 week cooldown.

---

[4] Insulator Seal, Inc.

4.5.2.4 System Repair

Should the hadron monitor fail and require replacement, the failed monitor will be disposed of. Given the intense activation of both the monitor and the surrounding shielding and absorber core, special care must be taken for personnel safety.

A conceptual idea for the sequence is indicated in **Figure 4.5-6**. The cables and gas lines for the hadron monitor protrude through the polyethylene blocks. Disconnections of these cables will be the first task. Provision for disconnections will be made just outside the absorber shielding. As the exterior of the absorber is expected to be 20 mRem/hr on contact after operations, this disconnection must be readily done.

Second, the two polyethylene blocks (not shown in the figure) must be extracted from the slot in the concrete shielding. They can be pulled out using pulley (A) and lowered down to ground level using pulley (B). Because these blocks will be activated they will be lowered into a shielded cart. The cart is rolled out of the passageway.

Removal of the hadron monitor is also accomplished using the two pulleys (A) and (B). Two steel cables will have been attached to the hadron monitor when it was inserted into the absorber and left attached to the hadron monitor (*i.e.*: they also protruded through the polyethylene blocks). These cables will be used to extract the hadron monitor (over pulley (A)) and lower it into a shielded coffin/cart (over pulley (B)). Because the cords were left attached to the HadMon during installation, the personnel can stand far away from the slot during this procedure. In **Figure 4.5-6**, the hadron monitor is shown at three successive locations during the procedure to extract it from the absorber (indicated as (1) through (3)).

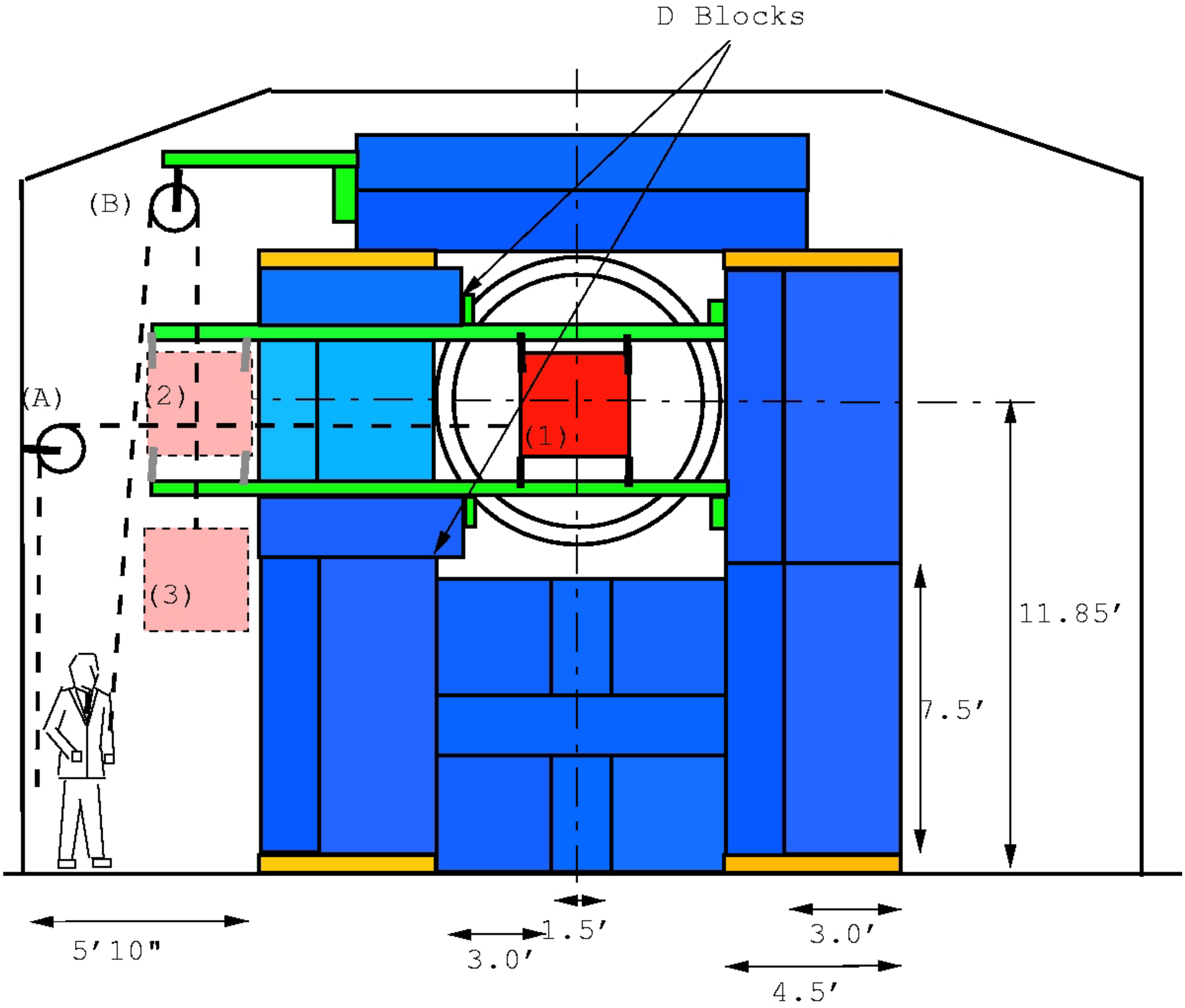

Figure 4.5-6 Rail and Pulley system for hadron monitoring replacement scheme as viewed from the downstream end of the absorber alcove.

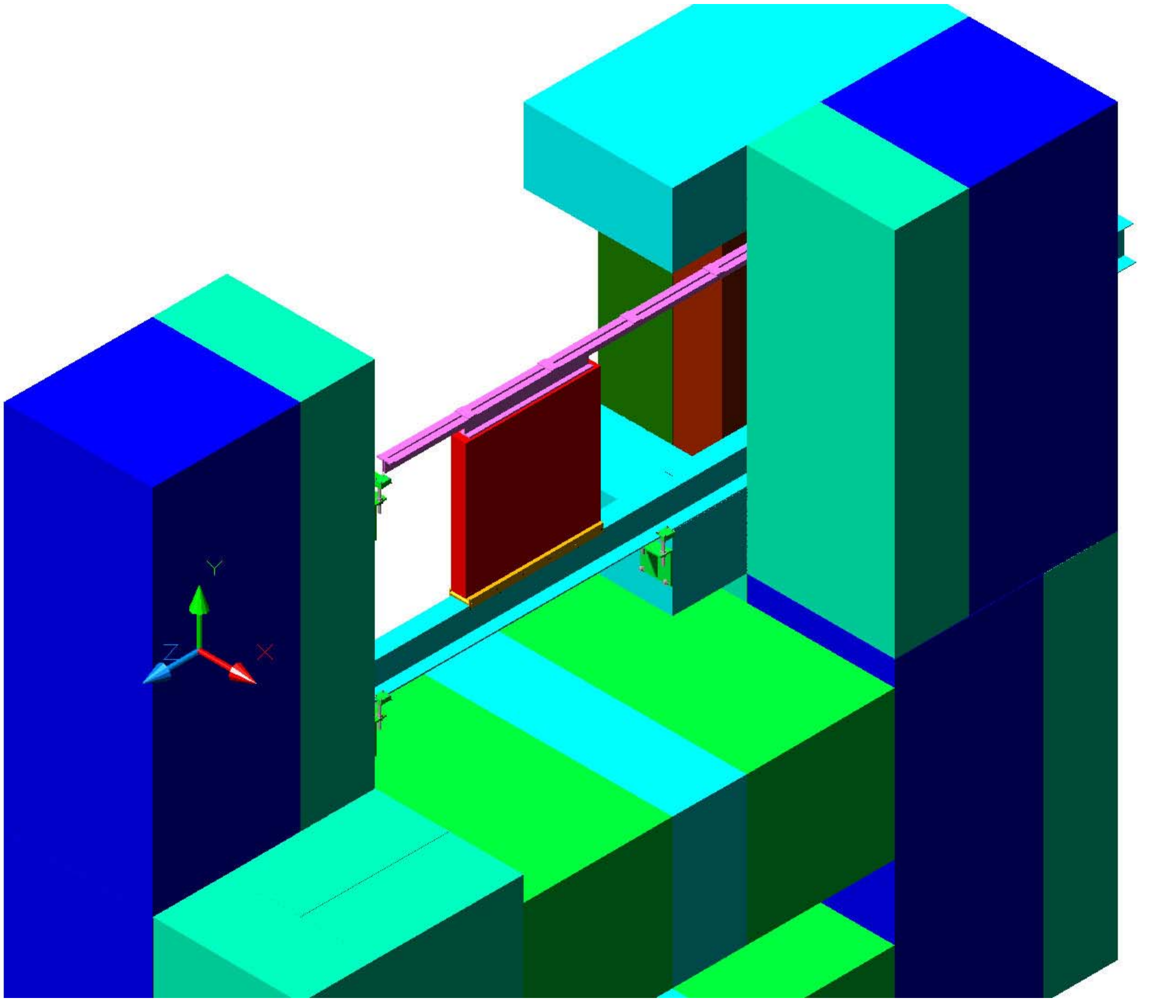

Figure 4.5-7 Rail system for hadron monitor replacement scheme.

The rail system to install and align the Hadron Monitor is shown in **Figure 4.5-7**. The lower rail is a 6” I-beam and supports the monitor weight. The monitor is in sliding contact with the rail. The upper rail consists of 6” “L” bracket that is straddled by fins on the top of the monitor so as to maintain verticality. A hard stop on the lower rail defines the fully-inserted monitor position, as well as the reproducible position to which replacement monitors may be inserted. Alignment and placement of the monitor is done during initial installation, but not after replacement.

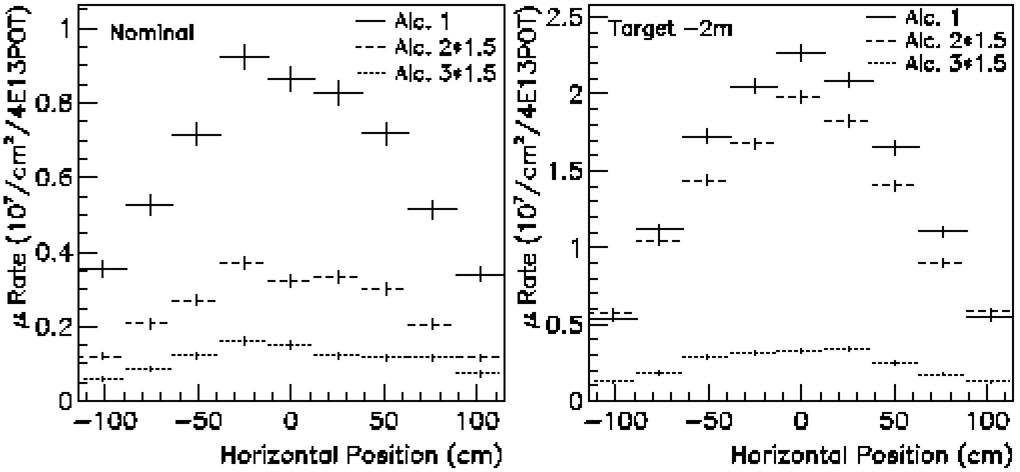

Figure 4.5-8 Muon fluxes in the 3 muon monitoring locations: Alcoves 1, 2 and 3 . Fuxes assume 4x 10^{13} protons on target per spill, and only include the muons, as predicted by GEANT. Shown are the fluxes in the three alcoves for nominal low-energy beam running (left plot), for special monitoring runs in the semi-medium energy beam (right). The fluxes in alcoves 2 and 3 have been multiplied by 1.5 (for both plots) so the shapes can been seen on the figure.

4.5.3 The Muon Monitors

4.5.3.1 System Function

The muon monitors are three arrays of ionization chambers located in the four 'alcoves' downstream of the hadron absorber in the NuMI beamline. Each alcove will see different fluxes of charged particles due to the attenuation expected in the absorber and dolomite rock between alcoves, with the downstream alcove seeing the most energetic muons only (see **Figure 4.5-8**).

The muon monitors are approximately 2 m by 2 m arrays of ion chambers that measure an ionized charge proportional to the number of muons passing through the array. Because each muon plane is segmented into an array of 9 by 9 chambers, the individual signals from each chamber in the array help locate the center of the muon (hence neutrino) beam. The chambers will not be absolutely calibrated to provide a charge-per-muon conversion factor, but will be relatively calibrated and this calibration will be tracked over time during operation of the NuMI beam. In this way, the relative signal seen from chamber to chamber indicates the relative magnitude of (muon) beam intensity at a particular location within each muon array, and also the comparison of rates between alcoves can be used to infer information on the energy spectrum of muons.

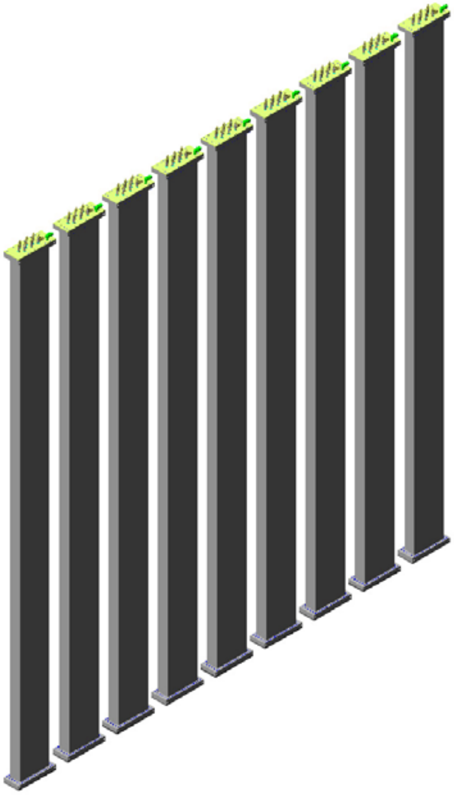

Figure 4.5-9 One array of 9 muon chamber tubes. Each tube is 2m in length, and separated from neighboring tubes by 25 cm (center-to-center).

An ion chamber tube is approximately 8 feet in length, made of 6" by 2" extruded aluminum tubing, 1/8" wall. Nine tubes will be used to form the 9 by 9 array (see **Figure 4.5-9**). The tube has 3/4" thick endflanges welded to each end to which are bolted endplates which handle all electrical and gas connections. The endplates are gas-sealed to the endflanges by an Aluminum wire gasket that is compressed by the endplate and endflanges.

The ion chambers themselves are mounted onto trays that slide into the tubes. A drawing of one of the ion chambers mounted on the channel is shown in **Figure 4.5-10**. The tray is rigidly bolted to one of the endplates via a tab (shown in red in the figure). The channel is shown in light blue, the endplate is shown in dark gray. The 6" by 2" tube and its endflange is also shown (in mustard brown). Not shown in the figure are the two kapton-insulated coax cables per ion chamber, which bring signal and HV to the chamber from the feedthroughs at the endplate.

The muon monitors use the same ceramic plate ion chamber electrodes as the hadron monitor. The gas gap, however, will be 3mm (not 1mm as in the hadron monitor). With this gas gap and Helium gas, it is anticipated to collect 1400, 170 and 80 pC per in the central ion chamber in Alcoves 1, 2, and 3, respectively.

The endplate with all electrical (signal and HV) connections is shown in **Figure 4.5-11**. The high voltage and signal feedthroughs are commercially-available ceramic-insulated vacuum feedthroughs. The signals for the 9 chambers are fed into a 9-pin D-type connector[5] with ceramic insulator, gold-plated stainless pins, and a stainless jacket. It is welded directly to the endplate. The high voltage (typically less than 600 Volts) is brought in through a straight-pin feedthrough.[6] One HV feedthrough delivers the HV for one chamber.

To maintain chamber-to-chamber calibrations over the course of NuMI operations, as well as help calibrate temperature or pressure variations, each chamber will have a 1 μCi Am^{241} alpha source (E = 5.4 MeV) mounted to it. During dedicated calibration runs, the electronics will trigger between NuMI spills so as to integrate the charge from the ionization created by the alpha's, not the NuMI beam. Such sources in bench measurements have been shown to ionize approximately 2.5pA of current in He gas, which is sufficient for calibration but a small background to actual beam spill measurements.

---

[5] Ceramaseal, Incorporated.

[6] Insulator Seal, Incorporated.

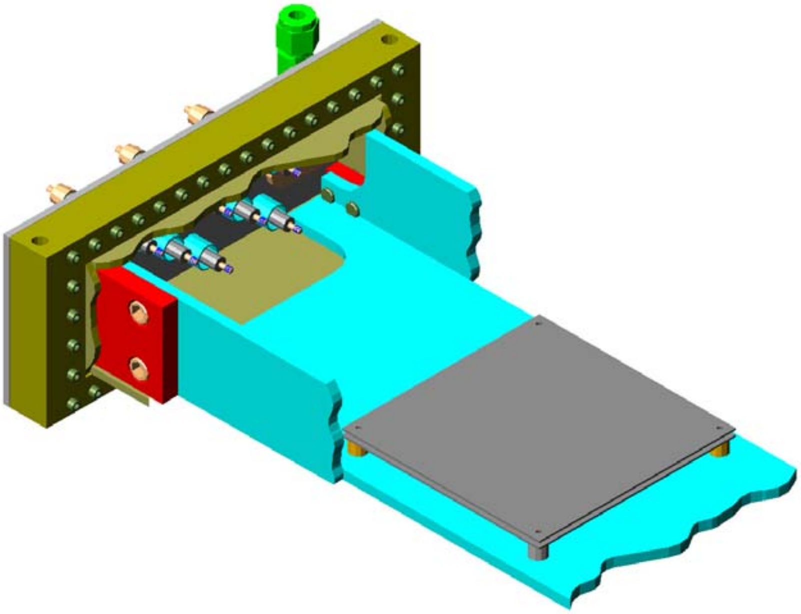

Figure 4.5-10. Tray inside a muon tube onto which the parallel plate chambers are mounted. Each ion chamber is connected to the electrical feedthroughs at the endplate by coax kapton cable (not indicated in drawing).

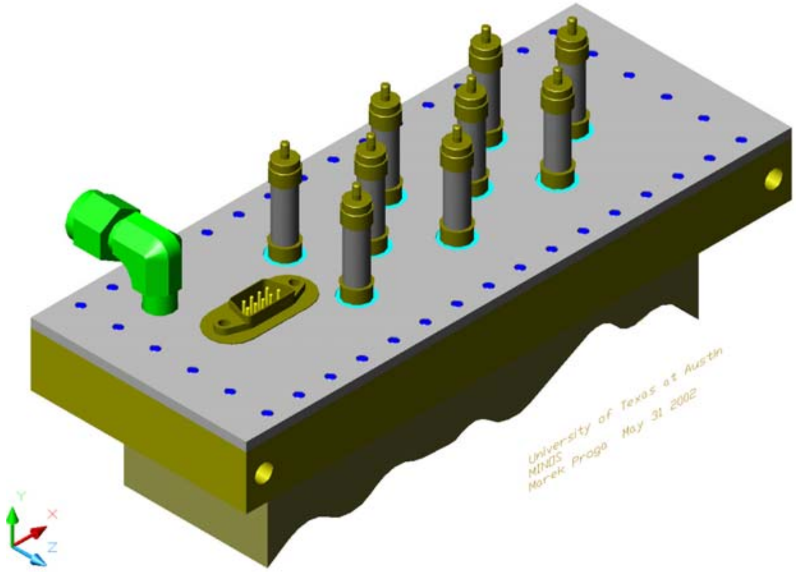

Figure 4.5-11. Endplate of the muon monitor tube will electrical feedthroughs. A single 9-pin D-type connector brings out the signal lines and a ceramic HV feedthrough is used for each individual chamber HV. A Swagelok feedthrough brings in the gas line.

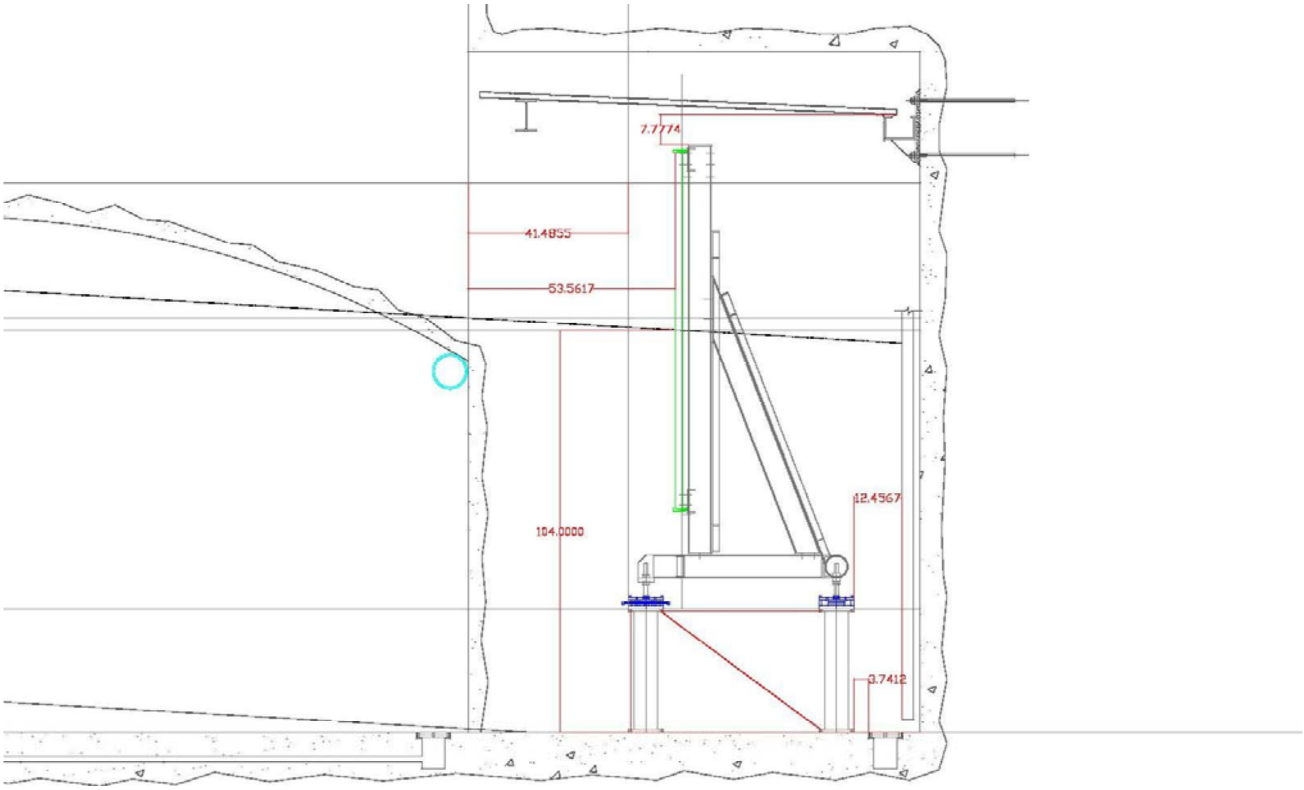

Figure 4.5-12. Elevation view of the support structure and the muon monitor in Alcove 1. The muon detectors are supported at beam center. The top of the detector is 7” from the drip ceiling.

A frame has been designed to support the muon beam monitoring chambers at beam height in any of four alcoves downstream of the hadron beam absorber. **Figure 4.5-12** shows a side view of this frame as seen in Alcove 1. Unobstructed access to the detectors is permitted from the upstream side for quick mounting or service of individual muon tubes. The chamber tubes hang by studs that fasten to the upper cross beam of the picture frame. The upper studs serve to locate the tube centers. Lower studs are less constrained in order to allow for welding inaccuracies and warp in the extruded tubes. We strive for 1 mm relative placement of the tubes on the frame. Cabling and gas supply will be routed along the bottom of the picture frame. Gas exhaust will be routed along the top of the picture frame. Deflection of the upper beam when loaded with the muon chambers should be about 0.050 inches.

Components of the frame are entirely aluminum except for steel jackscrews in the floor mounts. Because of the difficulty of transporting a frame to its final location underground, these frames have been made of smaller sections, which will be bolted together in the final alcove location. The three principal pieces are a rectangular picture frame on which the chamber tubes are mounted vertically, a diagonal bracing section which supports the picture frame, and a rectangular base section which has a 3-point mount on the floor.

Beam height in each alcove determines the vertical location of the frame. A single frame design should work well for all four muon alcoves. Jack screws in the feet allow a vertical adjustment of ±3 inches. Larger adjustments may be accomplished via extra bolt holes which allow the horizontal supports of the picture frame to be adjusted an additional amount vertically. Once the frame is bolted to the floor, no horizontal position adjustment is possible. The mounting frame is about 6 inches below the drip ceiling and 15 inches from the downstream wall. There exist about 52 inches of working space upstream of the muon chambers in alcoves 2 and 3. Part of this space may later be filled with light material (such as polyethylene) to reduce electrons in the beam flux.

4.5.4 System Description: Electronics

The essential features of the electronics used to acquire data are shown in the simplified schematic of **Figure 4.5-13**. An operational amplifier takes the signal and stores it on a precision 100pF integration capacitor. The voltage on the capacitor is subsequently digitized by an ADC for computer read-out. Voltage on the input to the integrator is maintained at a virtual ground subject to the limitations of the amplifier. This differs from pulse height read out systems that employ a load resistor to develop a voltage at this point in the circuit. The integration capacitors will be modified where necessary to accommodate the range in expected signal size. An additional resistor has been added across the common integrator output buses to eliminate cross talk for large signals.

The complete system used for data acquisition is the same as those used for SWIC Readout (**Figure 4.5-14)**. Each SWIC electronics box has 96 channels, each of the monitors use that same electronics (although the hadron monitor, of course, does not fill all the channels). There is a slight modification to the integration capacitor and an additional resistance is needed to reduce channel cross talk for large output signals. The integration time is to be 5msec.

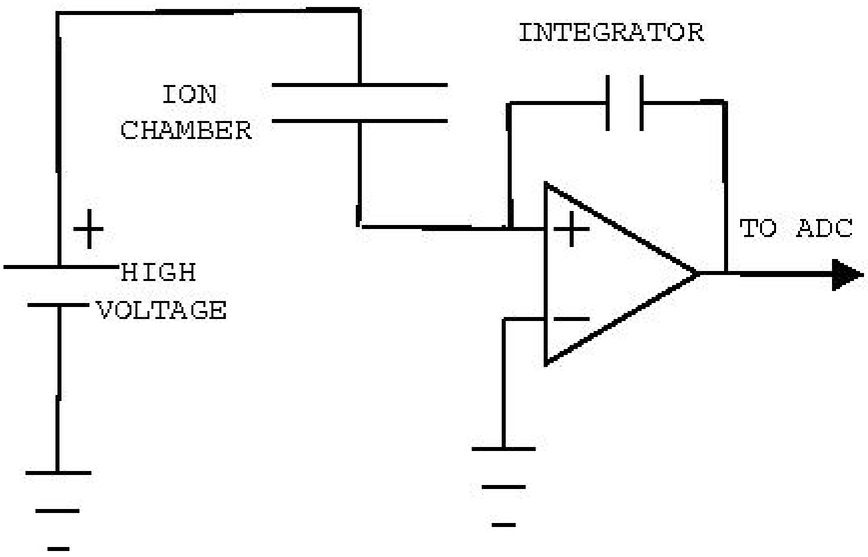

Figure 4.5-13: Schematic of ionization chamber and input stage of electronics

The map of where the electronics is placed can be seen in plan view in **Figure 4.5-1**. The electronics racks and high voltage are located in the bypass tunnel, which leads off to the west from the absorber cavern. Although the downstream hadron monitor is not shown in the diagram, both the hadron and the muon monitor in Alcove 1 will be serviced by SWIC controllers near the electronics rack. Electronics for all monitoring locations are accessible during normal running.

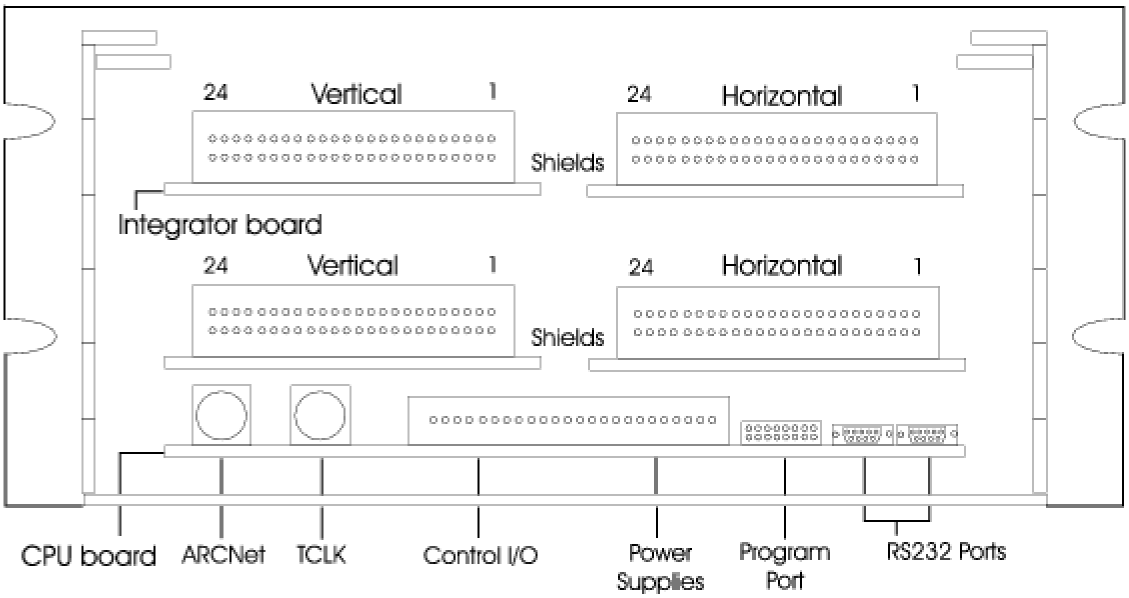

Figure 4.5-14 Layout of the 96-channel SWIC box.

4.5.5 System Description: Gas System

The monitors are to be supplied with helium, which must be maintained at a high purity (less than 10ppm impurities). Gas will be stored near the MINOS shaft, sent through a two stage regulator followed by a line filter to a gas distribution panel in the hallway near the electronics, which splits the one line to four, which then go to each of the four monitoring planes.
Exhaust gas is returned to the distribution panel where there will be bubblers, and then sent to an external vent, part of the HVAC system. **Figure 4.5-15** shows a schematic of the gas system.

There are two sets of “8-pack” high-pressure manifolds, one of which will be set up to a two-stage regulator. This allows operation in the semi-automatic mode, with one side in reserve at all times. The gas pressure after the two-stage regulator will be approximately 30psi. The gas will then be put through a line filter, and sent to the distribution panel near the electronics for the monitoring system. Each line going to a plane of monitors will be connected to two flowmeters in parallel, as well as a pressure gauge, and finally a valve to allow one to turn off the flow to only one alcove in case a muon tube needs to be replaced.

Gas is supplied to the main distribution rack located outside the last radiation barrier, via a continuous length of, 3/8" OD stainless tubing. The main distribution rack allows for adjustment of flow to a given alcove. Four sets of flow-meters control gas flow to each of the four monitoring planes. One flow meter will allow for fast purging of the monitor, while the other will be used for normal low flow running.

The chambers are to be operated at slight overpressure (<0.5 inches of water). Each tube has a gas volume of approximately 15 liters (three stations having total volume of 405 liters). The hadron monitor is 19 liters. Each bottle contains about 8000 l of gas, (300 ft^3). At the rate of one volume change per ~2hrs for all three alcoves plus the hadron monitor, we consume an 8-cylinder pack every week.

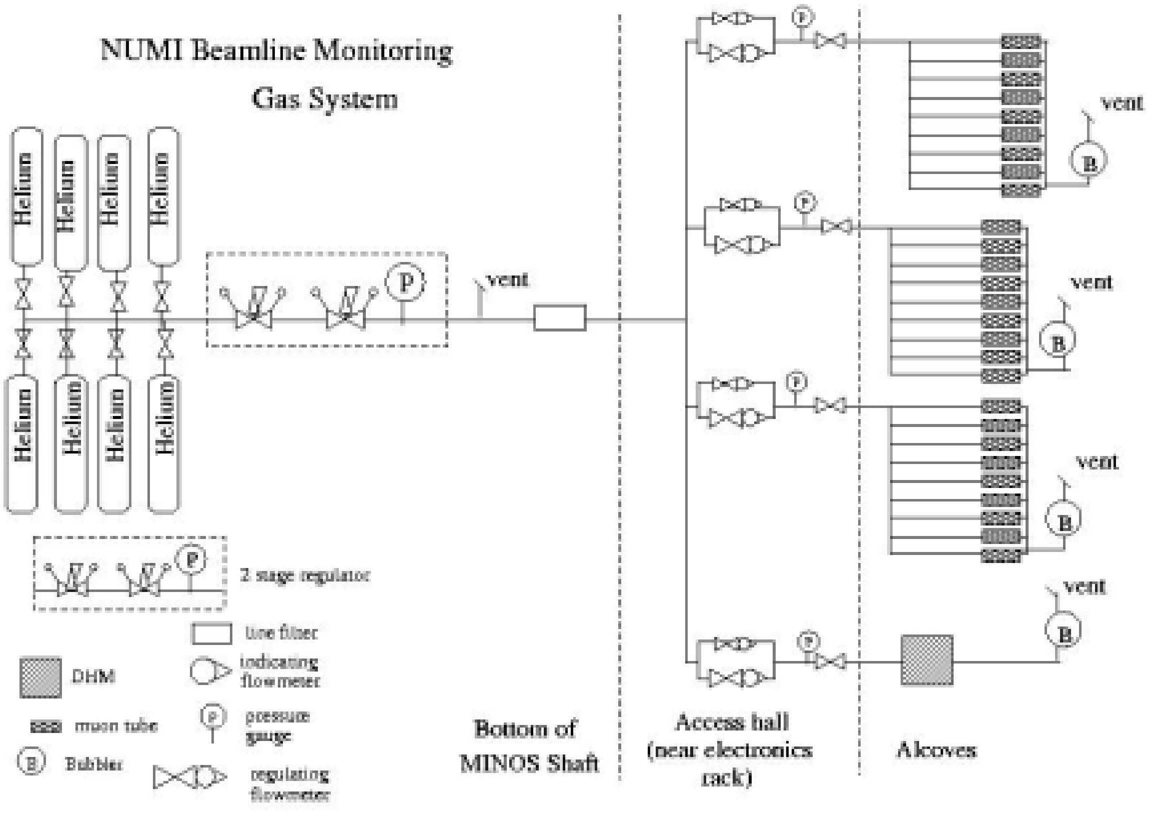

Figure 4.5-15 This shows a schematic drawing of the gas system.

4.5.6 System Description: Online Information

There is much information to be recorded during data taking to be able to ensure both that the monitors themselves are performing well, and ultimately that the beamline itself is performing as expected. Of course the information about the beamline is contained in the signals of these arrays, and the concurrent calibration constants that are to be calculated online. This information is to be summarized as an overall flux of particles (and a peak flux for the Downstream hadron monitor), and some shape information, including the first and second moments of the horizontal and vertical projections of the signals. The information that arrives at the monitors spill by spill will be transferred by the XML-RPC system which is currently also being used by MiniBooNE.

Because ionization chambers are used, we record signals from the detectors along with calibrations that are going on during off-spill gates. An ethernet controlled DAC sets voltages on 16 channels of modified Droege HV supplies. Seven of these supplies serve the Downstream Hadron Monitor. Each of the three muon alcoves is served by three HV channels. The current and voltage of each channel is read back over ethernet. Low voltages in the SWIC electronics and the HV NIM bins are also remotely monitored. Pressure, humidity, and temperature are monitored at the location of each detector. An overview of the ethernet system can be found in **Figure 4.5-16**.

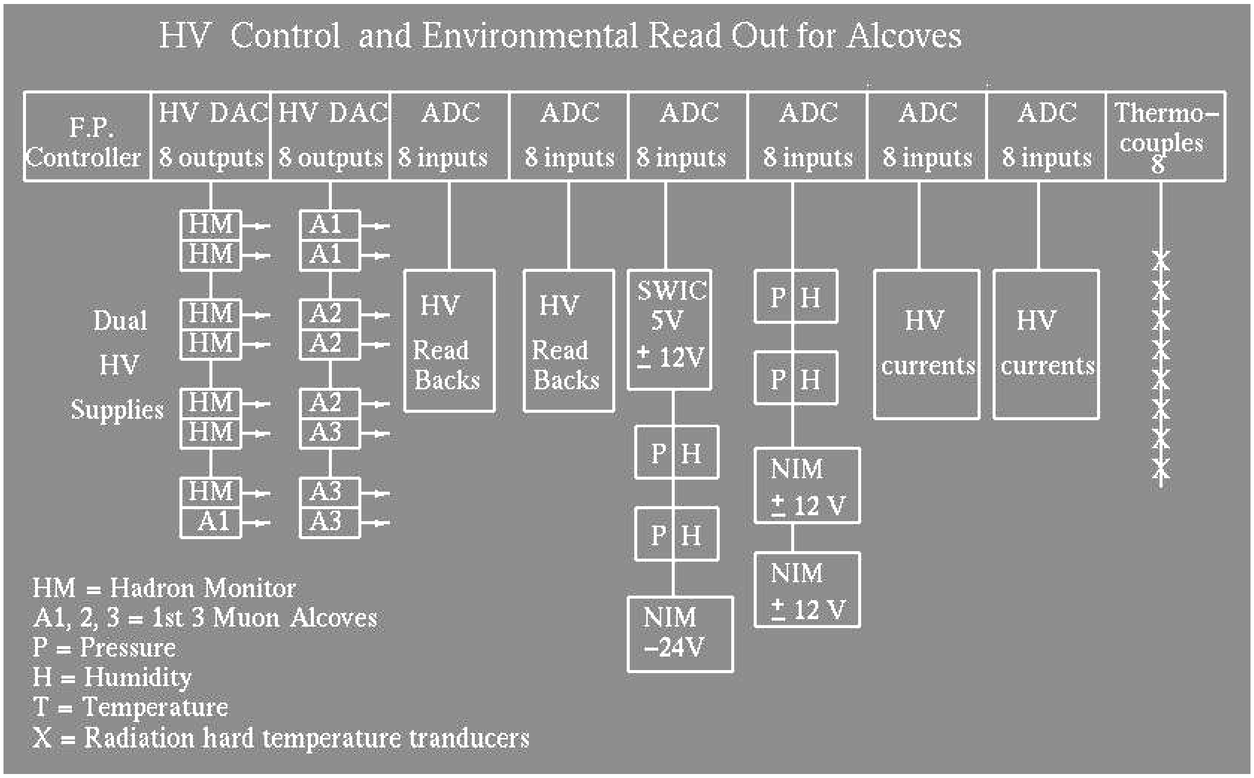

Figure 4.5-16 This shows the list of devices that DCS expects to get from the beamline monitoring devices.

The DCS will export its data to the rotorooter process and then on to the DISPATCHER where it along with the RPC XML data will be put in offline data streams, and will be available to the experimenters. Summary information will be put into the main ORACLE database by an offline job. In addition it is planned to store all the data acquired by the DCS on a disk of the DCS computer where time histories and correlations can be extracted if needed.