June 18, 2002

The Muon Monitor

Contents

1 System Description

The muon monitors are three arrays of ionization chambers located in the four 'alcoves' downstream of the hadron absorber in the NuMI beamline. At any one time of NuMI beam operation, one of the alcoves will be uninstrumented. During startup with the low-energy beam, it is anticipated to instrument alcoves 0, 1, and 2, where alcove 0 is the rear end of the absorber cavern. 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.

The muon monitors are approximately 2 m by 2 m arrays of ion chambers which measure an ionized charge which is 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

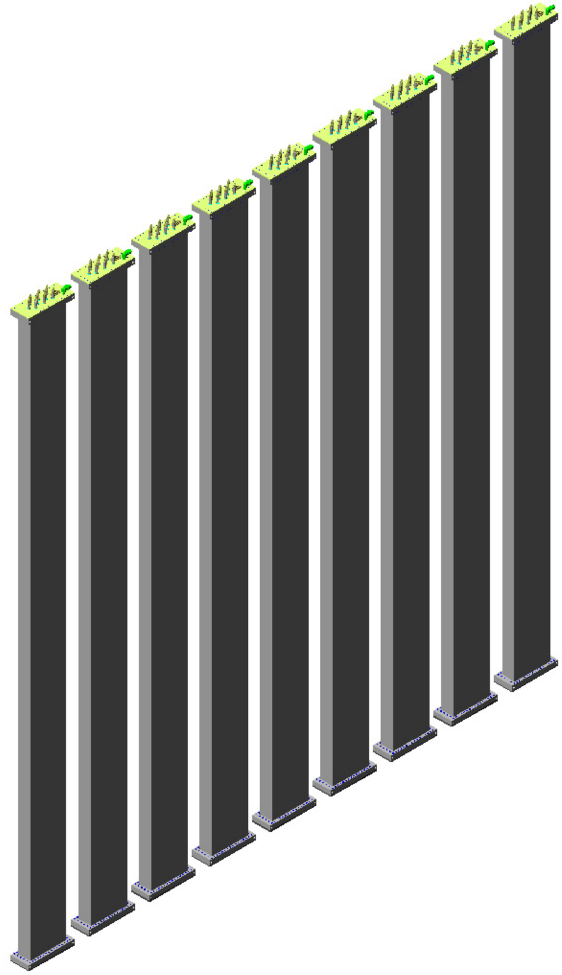

Figure 1: One of the three muon monitor arrays, consisting of 9 tubes each of which contain 9 ion chambers. All chambers in the array are spaced 10" center-to-center.

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.

In the NuMI low energy beam, the muon monitors see at the largest a flux of 4×10^7 charged particles/cm^2/spill and a radiation level of xxx MRad/year. In the high energy beam, these numbers are $xx \times 10^7$ charged particles/cm^2/spill and xxx MRad/year [1]. It should be noted that these numbers occur in the center of the beam in Alcove 0. The fluxes and radiation levels are substantially smaller at the edges of the muon monitor planes or in Alcove 2 (see [1]).

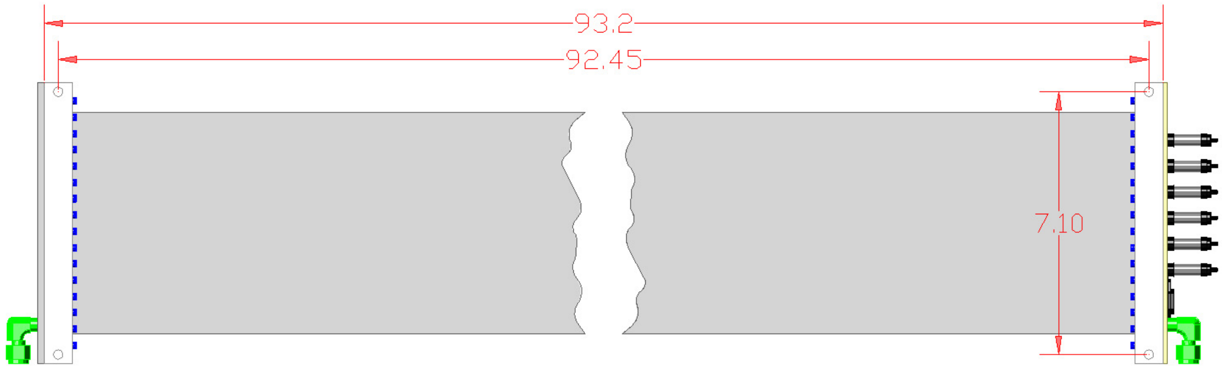

Figure 2: A single ion chamber tube. Each tube is fabricated from 6" by 2" rectangular tubing and contains 9 ion chambers spaced by 10". Endflanges are welded to the tube ends, and endplates with gas and electrical connections are bolted to these flanges. The tubes are mounted using 1/4-20 holes in the endflanges which are indicated.

2 System Layout

Each of the three muon monitor planes consists of 9 × 9 individual ionization chambers spaced 10" centerline-to-centerline. The ion chambers are housed in 'tubes', as shown in Figure 1. Each of the tubes houses 9 ion chambers lined up in a row. Each chamber in a tube is spaced 10" center-to-center from each other, and each tube in the plane is spaced 10" center of tube to center of tube.

The tubes in the three alcoves are all identical and thus interchangeable, should ever a tube need replacing. A total of 27 tubes are needed for the entire muon monitor system, and xx tubes will be constructed.

The tubes consist of 6" by 2" extruded rectangular Aluminum tubing. Each tube contains a tray on which the ion chambers sit and are slid into the tube. The tube has endflanges welded to each end. Endplates with all the electrical and gas connections to the tube are bolted to these endflanges. An exterior view of one tube is shown in Figure 2.

The tubes are to be mounted on a support structure which is the subject of a separate memo [2]. The mounting to this external support structure determines the tube-to-tube spacing as well as the alignment of the plane to the beamline center. The mounting to the support structure occurs via four 1/4-20 threaded holes which are drilled into the side of the endflanges, as shown in Figure 2. Drilled into the same endflanges on the opposite side are holes for tooling balls to align the tubes once on the support structures.

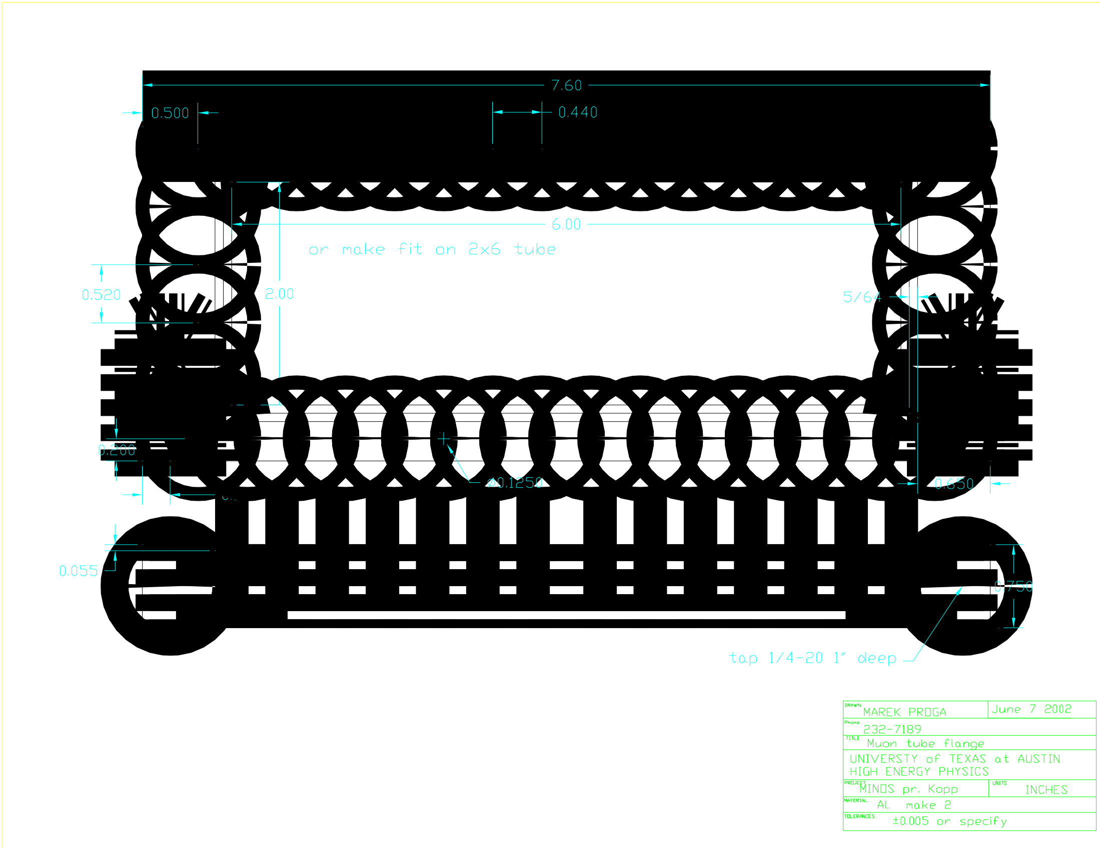

Figure 3: The Aluminum endflange welded to either end of the ion chamber tubes.

3 Ion Chamber Tubes

This section describes the layout of the tubes which each house a row of 9 ion chambers. The ion chambers themselves and their mounting are described in the next section.

An ion chamber tube is approximately 9 feet in length, made of 6" by 2" extruded aluminum tubing, 1/8" wall. The tube has 3/16" thick endflanges welded to each end to which are bolted endplates which handle all electrical and gas connections. Detailed drawings of the endflanges are given in Figure 3. The endplates are gas-sealed to the endflanges by an Aluminum wire gasket which is compressed by the endplate and endflanges.

The ion chambers themselves are mounted onto trays which slide into the tubes. Detailed drawings of the channel are shown in Figures 4-6. The channel is made from 5" by 2" aluminum "U" channel which is machined down to dimensions of 5" by 1.75" so it fits inside the tube. One end of the channel (the right edge in Figure 4 and hereafter referred to as the "B" end of the channel) is rigidly bolted to the endplate on that end of the tube and the endplate+tray is slide into the tube. The endplate is attached using the 1/4-20 holes on the sides of the "U" channel which are indicated in Figure 5. A cut-out in the channel at this

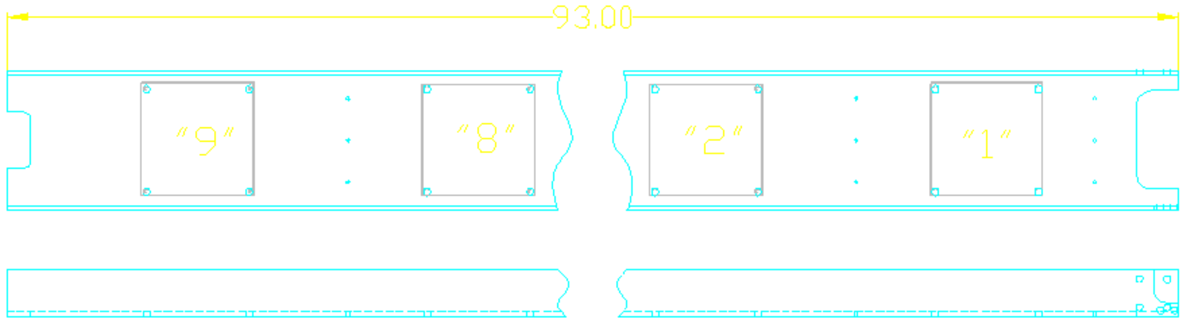

Figure 4: The 5" by 1.75" "U" channel onto which the ion chambers are mounted. Shown are top and side view of the channel, with overall dimensions and locations of square ion chambers.

end allows the cables to be routed to the endplate feedthroughs.

The other end of the channel (hereafter referred to as the "A" end of the channel) is not bolted to its nearby endplate, but is instead clamped to the tube wall. This end, the left edge of Figure 4 which is shown in greater detail in Figure 6, also has a cutout which is used to allow bolts to pass through the channel into the tube in such a way as to allow some flexibility of final positioning. All position referece, in other words, is from the "B" end of the channel shown in Figure 5.

The chambers are bolted to the channel at their four corners using the 1/4-28 tapped hole patterns shown in Figures 5 and 6. In between the chambers are 6-32 tapped holes used to clamp down the signal and HV cables which all come from the edge of the channel shown in Figure 5.

Figure 7 shows a cutaway view of the "B" end of the channel after it has been bolted to the endplate and the assembly slid inside the tube. The endplate on this end has all the signal and high voltage feedthroughs on it, as well as the gas inlet (a Swagelok fitting shown in light green in the figure). The endplate has welded to it two plates (shown in red) which protrude into the tube and to the sides of the "U" channel are bolted. Thus, the channel is first bolted to this endplate, then the assembly slid inside the ion chamber tube, and the endplate bolted to the tube's endflange.

Figure 8 shows how the other end of the channel, the "A" end, is clamped to the tube. This end has no cables passing through it. The channel has a large cutout in its 5" side that acts as a very large clearance hole. The tube will have a plate that is .170" in thickness welded to the tube wall. The plate is slightly thinner than the channel wall thickness, which is 3/16". The plate has two tapped 6-32 holes in it. The channel slides around this plate because of the cutout in the channel (shown in Figures 4 and 6). A large 'washer' plate is made with two clearance holes for the 6/32 screws and this washer plate clamps the "U" channel down to the tube once the bolts are tightened into the welded plate.

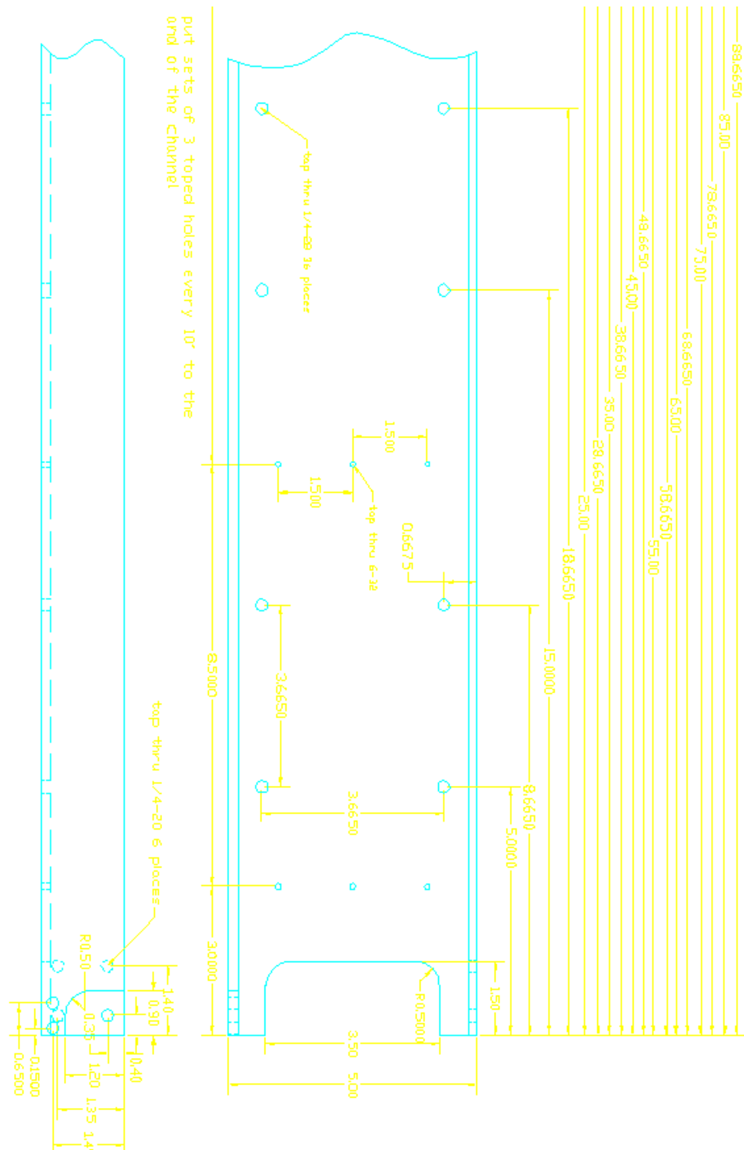

Figure 5: Detail view of right edge of channel in Figure 4, top and side views. This is the end to which the channel is bolted to the endplate with electrical feedthroughs. This end is referred to as the “B” end of the channel.

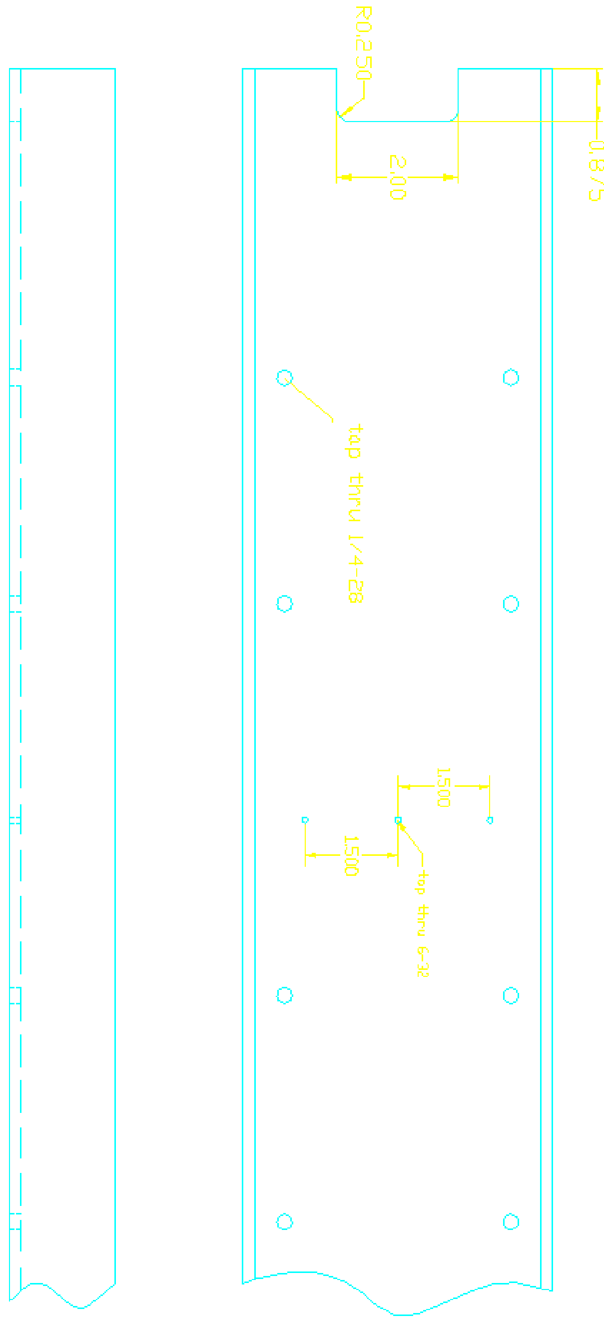

Figure 6: Detail view of the left edge of the channel in the Figure 4. This is the end that is clamped down to the tube (see text). This end is referred to as the “A” end of the channel.

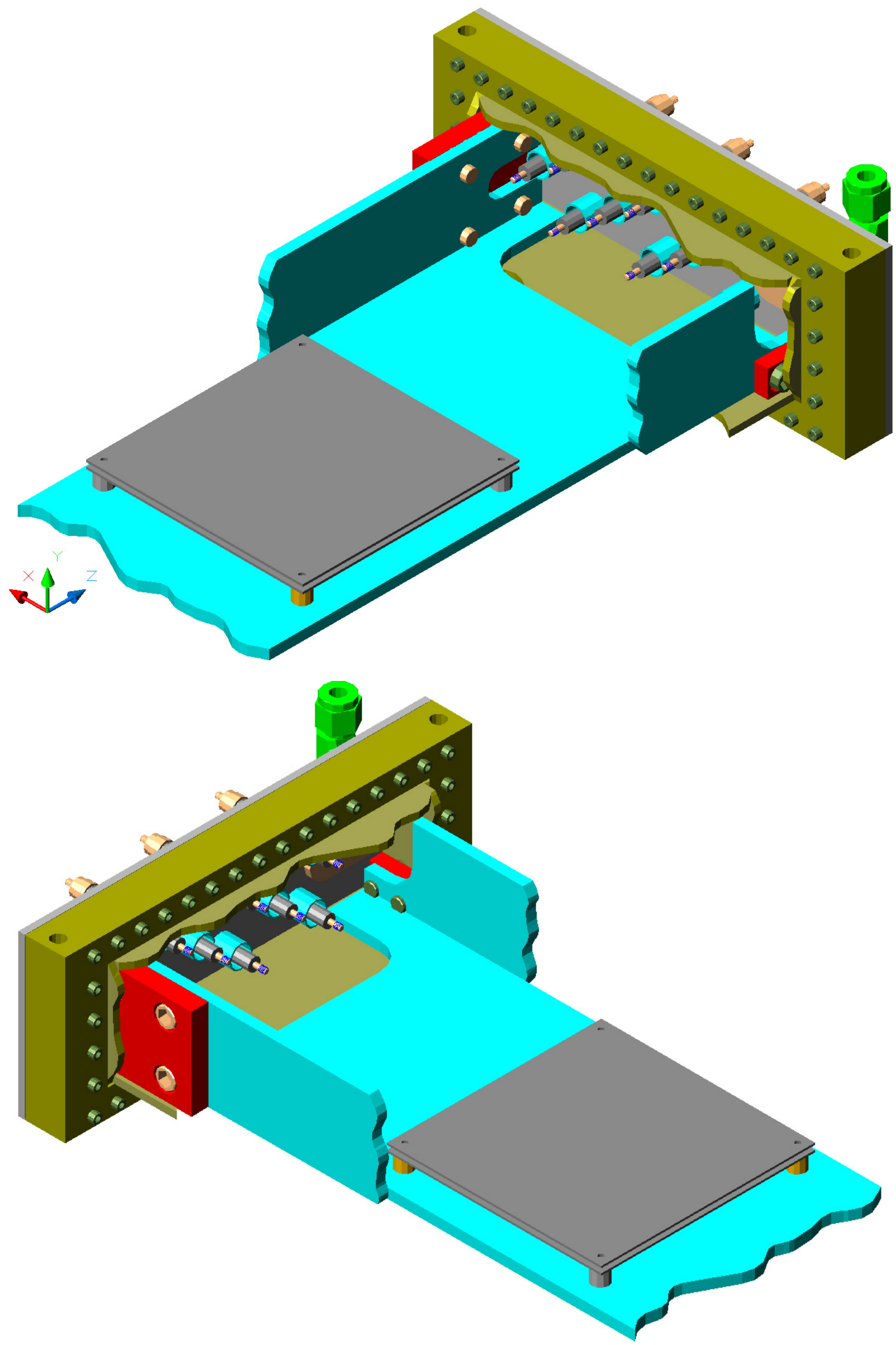

Figure 7: Two cutaway views of the “U” shaped channel on the “B” end, which is bolted to the nearby endplate. The channel is shown in light blue, the endplate is shown in dark gray. Two plates welded to the endplate are shown in red, and these have countersunk holes for bolts to attach to the channel. The 6” by 2” tube and its endflange is also shown (in mustard brown). Note that the heads of the bolts which secure the endplate to the endflange are seen in these views (ie: the endplate is tapped).

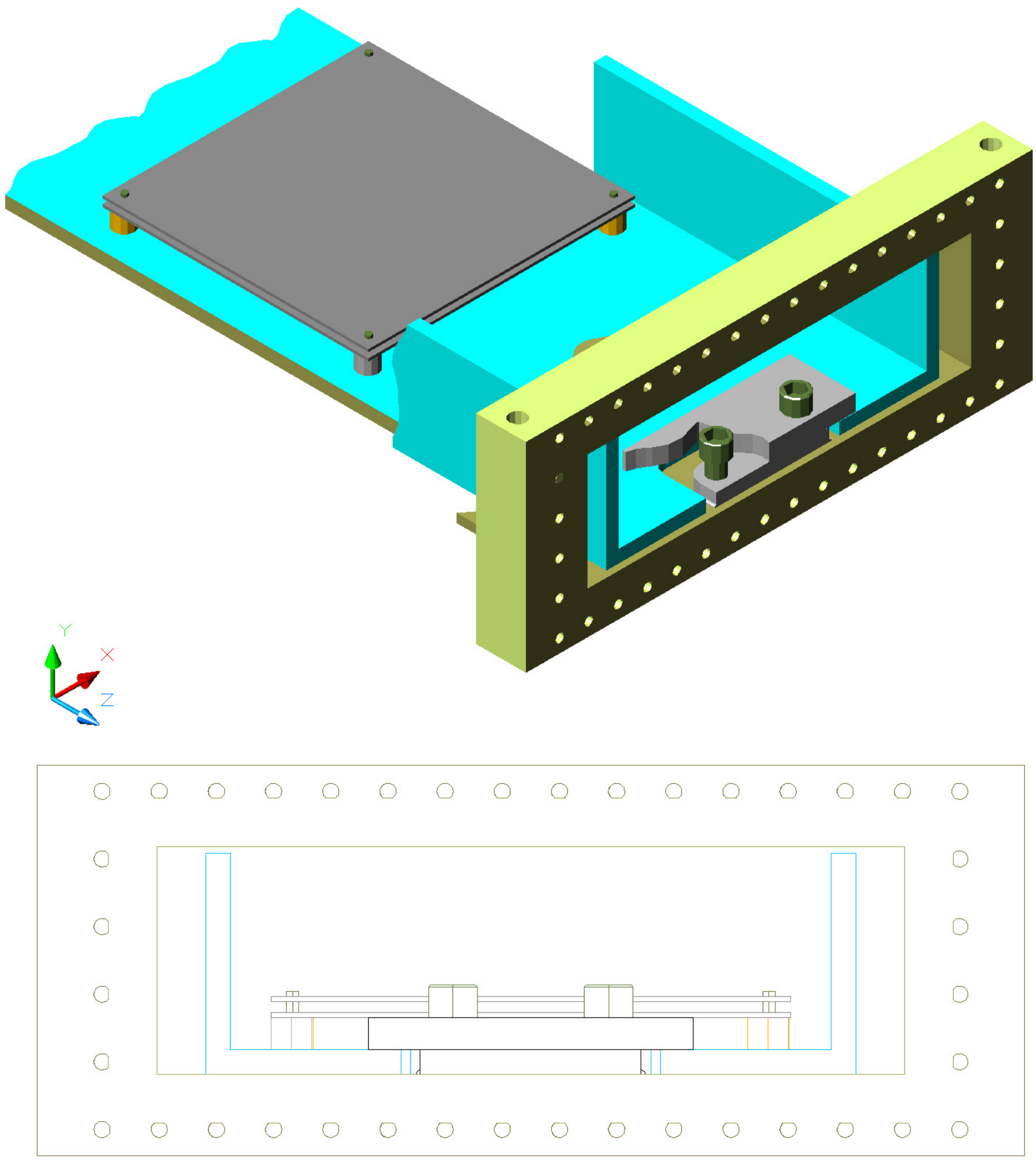

Figure 8: Two views of the "U" channel on the "A" end, showing how it is bolted to the tube. A 0.170" thick plate with 6/32 tapped holes is tack-welded to the tube wall. The channel slides around this plate. Two bolts clamp the channel to the tube by compressing it between a large 'washer plate' and the tube wall.

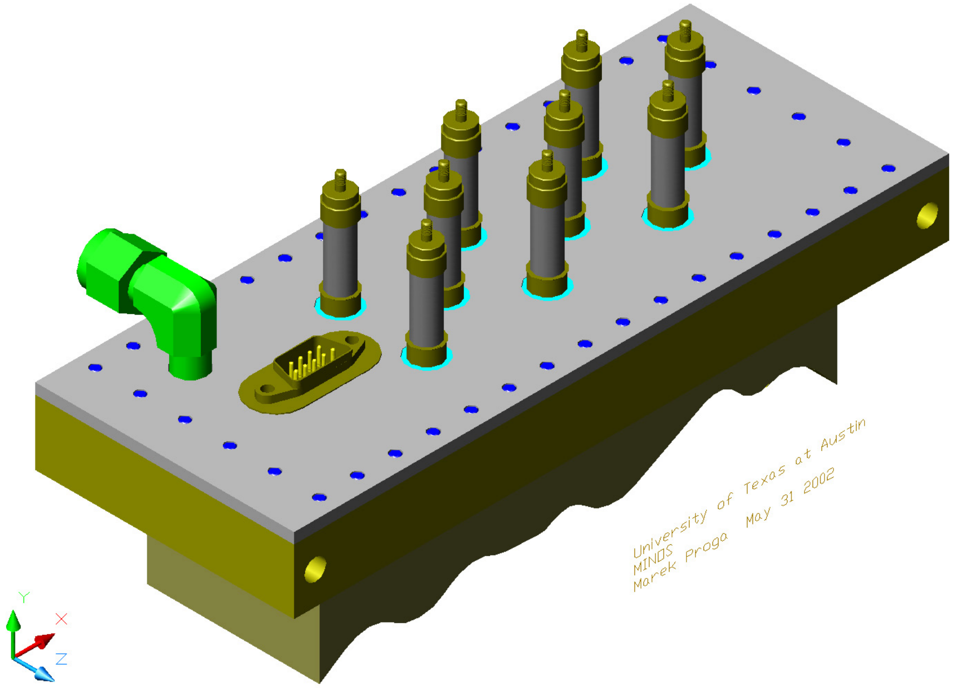

Figure 9: View of the exterior of the stainless endplate which has all the HV and signal feedthroughs. The signals are brought in through a ceramic-insulated 9-pin D-type connector while the HV lines (1 per chamber) are brought in through ceramic-insulated straight pin feedthrough. Also visible is the gas input (a Swagelok elbow) and the bolts which thread into the endplate from the endflange on the tube.

4 Electrical Feedthroughs

The endplate with all electrical (signal and HV) connections is shown in Figure 9. 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[1] with ceramic insulator, gold-plated stainless pins, and a stainless jacket. This jacket is then welded to the endplate, which is also made of stainless steel. A view of the endplate is given in Figure 10. The high voltage (typically less than 600 Volts) is brought in through a straight-pin feedthrough[2]. One HV feedthrough delivers the HV for one chamber.

Inside the tube, the signals are routed from the ion chambers to the endplate using coaxial kapton cable.[3]. The 9 signal cables are brought to the endplate and soldered into a the pins of a female D-type connector which is made of PEEK insulating plastic. PEEK and kapton, as discussed in Section 11, is rad hard at the level required [1] in the muon

[1]Part number xxxx, fabricated by Ceramaseal, xxxx, USA.
[2]Part number xxx, fabricated by Insulator Seal, Incorporated, Hayward, CA.
[3]Fabricated by W. L. Gore and Co., xxxx, U.S.A.

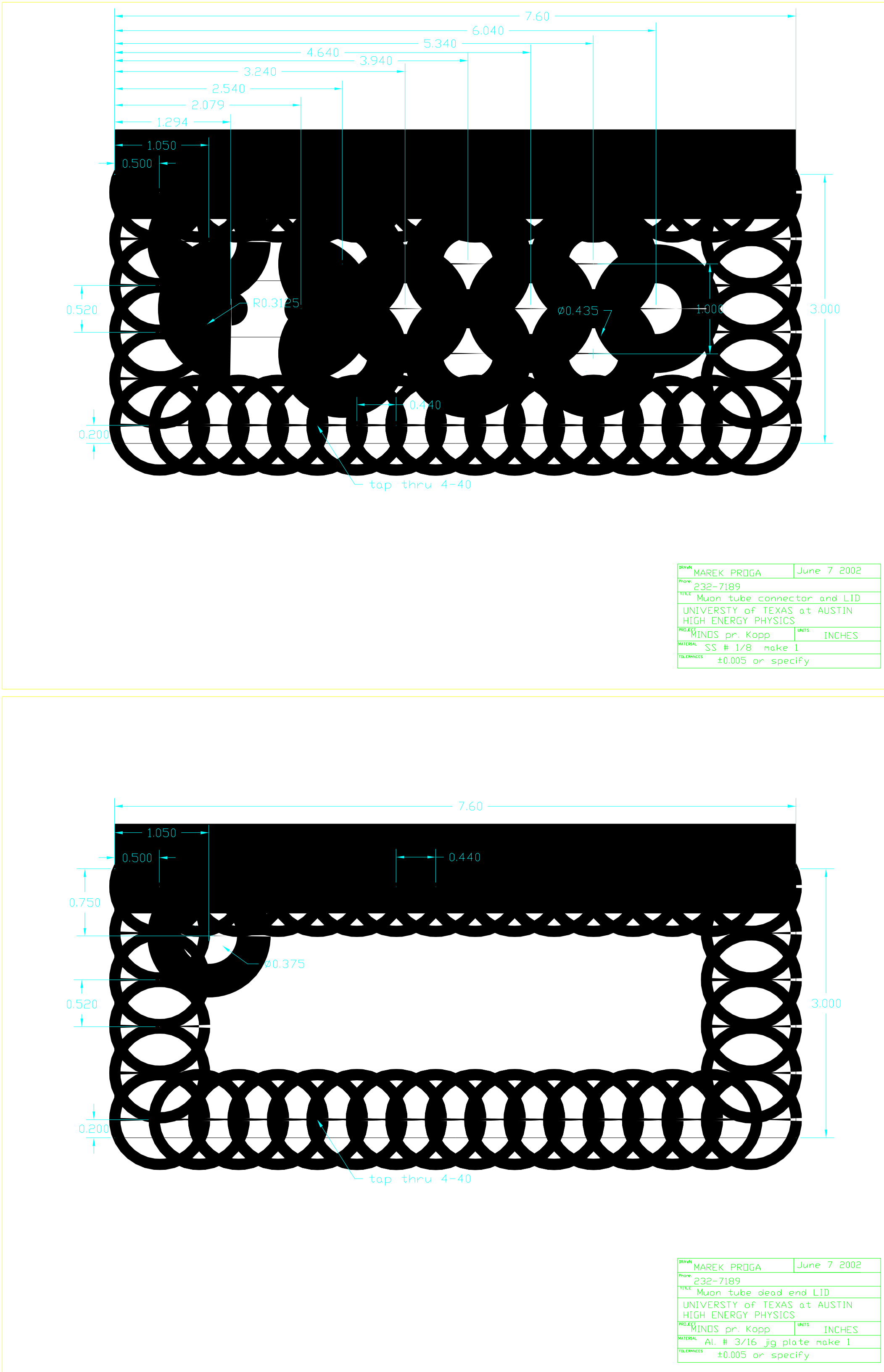

Figure 10: Drawings for the stainless steel endplates.

alcoves, and is known to be quite low in outgassing. The PEEK connector, in addition to allowin us to disconnect the signal lines from the end plate rather trivially, serves a very important signal-protecting function: it completely covers the pins of the feedthrough and prevents the interior gas volume from seeing the signal lines. This is very important because the entire gas volume (inside and outside the tube) is being ionized by the NuMI beam, and 'stray' ionization (ionization which occurs outside the gaps of the actual ion chambers) can collect on the signal lines, contaminating the signal from a given ion chamber.[3]. The kapton coaxial cable used for both the signals and the HV lines also helps shield from stray ionization effects.

On the air-side of the endplate, an ordinary D-type female connector is to be mated to the male feedthrough. RG-174 cables will go into the D-connector, and the solder connections potted to again prevent against stray ionization. Because this is on the air side, the materials are less critical from the point of view of outgassing. The HV feedthroughs will be simply soldered to RG-174 cable. In order to protect personnel from the exposed HV of the feedthrough central pin, this will be wrapped in kapton tape. It is possible to construct a small cage over this endplate to protect the feedthroughs from mechanical shock, as is being done for the hadron monitor.

5 Ion Chamber Plates

The muon monitor planes consist of an array of parallel plate ionization chambers [4]. Figure 11 shows the drawings for the ceramic plates of the parallel plate ion chambers. The wafers are 1 mm 99.7% pure Aluminum oxide, with 0.0005" thick Pt-Ag alloy electrodes. The electrodes are bonded to the ceramic substrate by baking at 1700°F after a photolithography process is used to lay the metal alloy paste on the substrate.[4], and are made using the same process as test pieces used in beam tests in Oct-Nov. 2001.[5] Electrical connections to the grounded gaurd 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. Typical flatness of the pieces, based on a preliminary order of 20 boards, is less than 0.003" across the 4" plate. The chamber plates are separated from one another by xx mm ceramic washers which are laser-cut to a precision of 0.001". The same ceramic circuit boards are used for the hadron monitor.

6 Connections to Chambers

It is important to make the connections (signal and HV) to the chamber plates in a way that shields these connections from the surrounding gas volume. The connections will be concealed inside the support posts that bolt the parallel plate chambers to the "U" shaped tray that slides into the tube. Four support posts are used to mount each parallel plate

[4]The plates are fabricated by Cer-Tek of El Paso, TX

[5]Test pieces developed at Amitron, Inc., North Andover, MA.

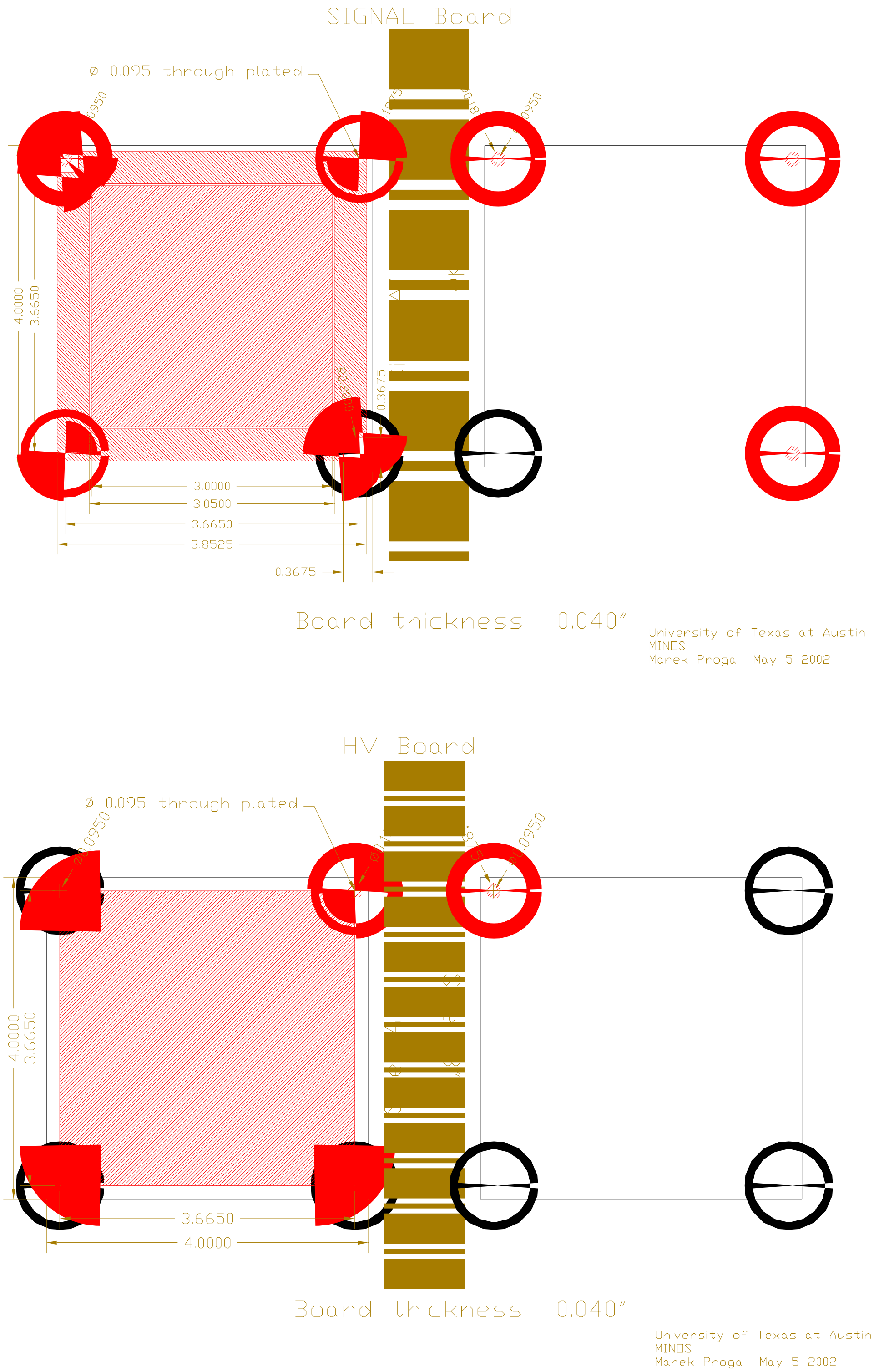

Figure 11: Drawings of the ceramic wafers that comprise the parallel plate ionization chambers. Above: the signal board, with 1 cm gaurd ring. Below: high voltage board.

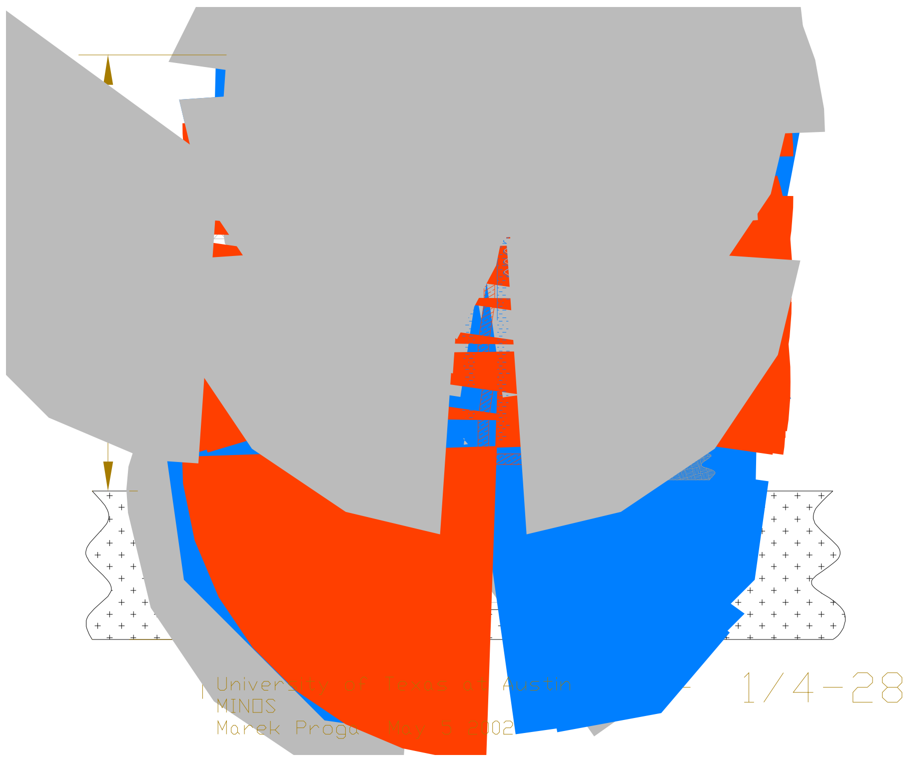

Figure 12: The mounting of the parallel plate chamber to the "U" shaped tray showing the signal or HV connection being made through the support post.

chamber. Each chamber will have its signal plate mounted closest to the channel, with the HV plate mounted after.

Two of the support posts are made of Aluminum and make the ground contact for the gaurd ring at the two corners shown in Figure 11 which connect to the gaurd ring. The Aluminum posts are 0.25" tall, have a 1/4-28 thread into the channel, and have a #2 threaded stud sticking up which is soldered to the gaurd ring corner. The ceramic washers are placed over the studs, the HV plate placed on top, and a threaded cap placed over the stud to compress the HV plate down onto this assembly.

Figure 12 shows one of the two support posts which is used to connect HV or signal to a chamber. The post is made of PEEK plastic, and has a central threaded hole for a #2 threaded stud to be inserted from the top. This stud is made from stainless steel tubing, and the kapton cable from the feedthrough plate is routed up the central part of this stainless stud and soldered at the top of the stud. The grounded jacket is stripped back so that just the central conductor is routed up the stud. The threaded stud is soldered to the corner contact pad on the ceramic circuit board. In the drawing of Figure 12, the solder connection is being made to the HV plate, so the solder is on the non-chamber (top) side of the HV (upper) plate. A PEEK cap is threaded over the stud's top to shield the HV from the gas volume.

In Figure 12, the kapton cable enters the drawing from the right, the outer conducting

Item	Material	Dimensions	Volume (in^3)	Number per Tube	Mass (lb.)
Tube	Al	6"×2"×95" 1/8" wall	103.6	1	10.1
Tray	Al	5"×1.75"×94.5" 3/16" wall	144.0	1	14.0
Endflange	Al	7.6"×3.6"×0.75" 2.0"×6.0" hole	11.5	2	2.2
Endplate(signal)	Stainless	7.6"×3.0"×1/8"	2.9	1	0.8
Endplate	Al	7.6"×3.0"×3/16"	4.28	1	0.4
Chamber Plates	ceramic	4.0"×4.0"×0.040"	0.64	18	1.6
HV Feedthroughs	-	-		9	0.2
Posts, cables, ...					2.0
Total Mass					31.3

Table 1: Tabulated dimensions, volumes, and masses of components in the muon monitor ionization chamber tubes. The densities assumed were Al: 0.0973 lb/in^3, Stainless: 0.28 lb/in^3; ceramic: 0.14 lb/in^3.

jacket of which is represented in grey, the dielectric is represented in white, and the central conductor is represented in red. The central conductor is inserted in a hole in the PEEK support post from the side. The PEEK is shown in white with hatching. The kapton cable central conductor is routed up a stainless threaded stud (shown in blue) and soldered to the stud at its top. The solder connection to the HV plate is shown by a grey blob at the top of the HV plate, and the PEEK cap used to shield the HV stud from the gas volume is shown in the same white with hatching as is the PEEK post. Note that a grounded tube surrounds the post to protect the signal/HV from the surrounding gas volume (tube shown in purple).

A similar procedure is followed for making the signal pad connection, except the solder is applied to the chamber (upward-facing) side of the signal plate (lower-plate in the drawing of Figure 12). After this electrical connection is made, the ceramic washer is placed over the top of the stainless #2 stud, the HV plate laid on top, and a PEEK cap used to constrain the HV plate down onto the support. Note that the PEEK cap also protects the stud, which is at signal potential, from the surrounding gas volume.

7 Mass of Ion Chamber Tubes

In order to define the total mass to be supported by the monitoring chamber support structures, we tabulate the total mass of all the components in a single ion chamber tube in Table 1. Note that 9 tubes are mounted to one support structure.

8 Alignment and Survey

something about tooling balls on the endflanges, errors on all the dimensions....

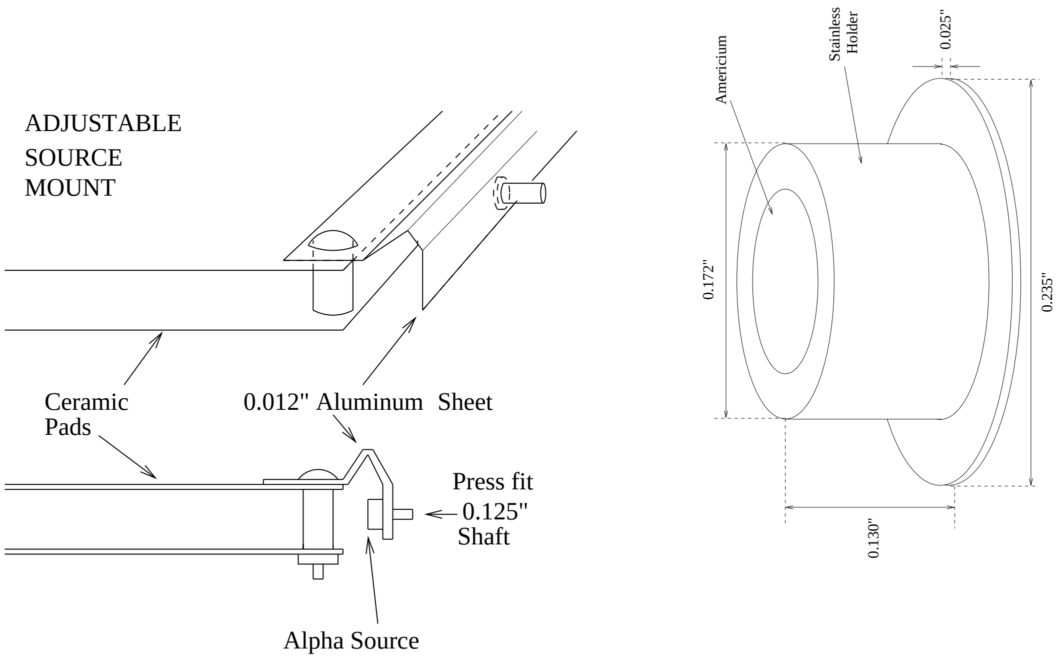

Figure 13: (left) Schematic diagram of an alpha source mounted to the side of the parallel plate ionization chambers in the muon array. (right) Diagram of the actual Am^{241} source encased in it stainless steel housing.

9 Calibration Sources

Each chamber will have mounted to it a 1 μCi ^{241}Am source. The Americium is an α emitter with $\langle E_\alpha \rangle = 5.5$ MeV. The ionization signal from this alpha will be used to study the response of the chambers over time and help calibrate any temporal variations in the ionization signal which could arise from pressure or temperature variations. It is desired to preserve the initial chamber-to-chamber pre-calibration at the 1% level over the course of the NuMI run, thus the source long-term calibration must be accurate at this level. Every chamber in the muon system will have such a calibration source. A schematic of the source and its mounting to the ion chambers is shown in Figure 13.

The expected signal from such a calibration source can be roughly calculated. The range for such an alpha is approximately 20 cm in Helium gas [6], ionizing typically 1200 electron-ion pairs per centimeter along its track[7]. With a 1 μCi = 3.7×10^4 disintigrations/second source mounted at the edge of a 4.5"×4.5" chamber of 5 mm gap (corresponding to 5 mm×4.5"/4.5"^{2}=0.01 solid angle), and assuming a 3 cm path length average over the sense pad, we expect approximately 7.5 pA of ionization current. If the signal is integrated during the spill, this contributes a negligible error to the beam spill measurement, but if measured between spills (1.8 sec) gives a reasonable calibration signal.

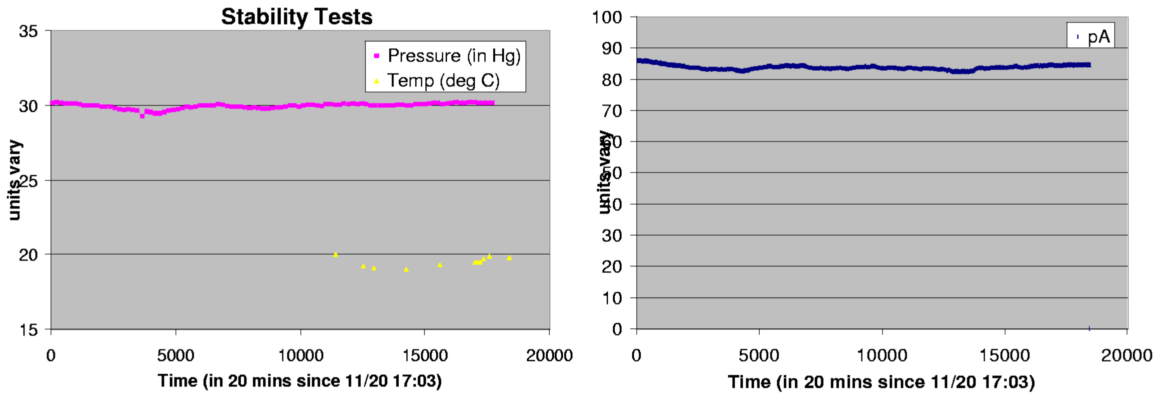

Figure 14: (left) The signal on a 5 mm gap ion chamber exposed to an Am^{241} alpha source for 2 weeks while being flushed with pure He gas at xx" H_2O over atmospheric pressure. (right) The barometric pressure during this same time, as reported at the Austin airport.

Figure 14 shows the stability of operation of a 5 mm ion chamber over 2 weeks' time. The chamber had several Americium sources illuminating it, so drew a steady current of 84 pA from a Keithley 485 picoammeter. Also shown in the figure is the barometric pressure reported at the Austin airport during the time of operation. The chamber was held at a constant 0.5" water pressure above atmosphere during this time. As can be seen, the trends in the chamber signal track the barometric pressure. During this time the mean ionization current was 84.0 pA, and the RMS was 0.70 pA. Thus, it appears likely that chamber variations introduced by variations in barometric pressure should be below 1%, and on top of that fact this variation should be readily measureable.

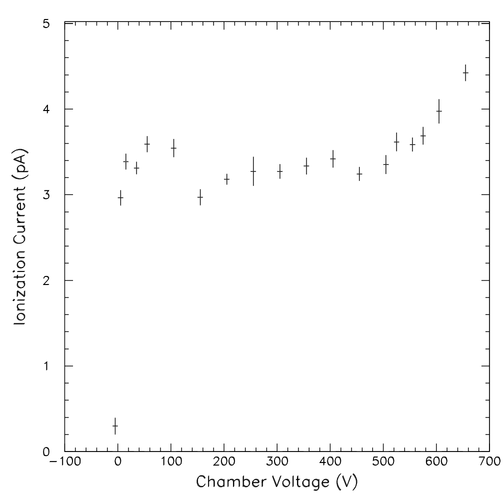

Figure 15: High voltage scan of a 5 mm gap ion chamber with a 1 μCi Am^{241} smoke detector source mounted to it under He gas flow.

The actual calibration signal will be substantially weaker than that shown in Figure 14, since only one source will be used. Figure 15 shows a plateau curve of a 5 mm chamber with a 1 μCi source mounted to it while being flushed with pure Helium gas. A plateau curve is a scan of the applied voltage on the chamber from 0 V up into the gas amplification region. On 'plateau' where our chambers are to be operated, the full ionized charge is collected on the signal electrode without any amplification in the gas while the charges drift. As expected, the current signal on ionization 'plateau' is approximately 3.5 pA, so the detector calibration accuracy will depend critically on the quality of the charge readout electronics. In this test, a Keithley 485 picoammeter was used, while in the NuMI beam so-called SWIC scanners [8] will read out the chambers. It must be demonstrated that the noise on the scanners is suitable for our calibration purposes.

10 Radiation Safety

There are two aspects of radiation safety which we will discuss briefly.

The first aspect concerns the shipping of the monitor tubes to Fermilab. The muon monitor tubes will be shipped to Fermilab after assembly offsite. The tubes will contain 9 radioactive sources which are the calibration sources for each of the contained chambers. Fermilab has agreed to receive these tubes with certain provisions. First, the university Radiation Safety Officer must notify Marie XXXX of Fermilab ES&H of the intent to ship the tubes to Fermilab and also provide verification of the contained source type and activity. Second, Fermilab must at that time notify the university RSO of the proper address at Fermilab shipping and receiving. Third, the university RSO must then be the official shipper of the tubes. Fourth, the tubes must be tagged as containing a radioactive source, indicating source type and strength. Given the eventual environment the tubes will be placed in, the tags should be metallic. Finally, after receipt at Fermilab, ES&H must accompany the tubes every time they are moved from one building on the Fermilab site to another.

Discussions have already occurred with the University of Texas RSO, Scott Pennington *Note: need to coordinate Pitt RSO.* He assumes full responsibility at UT for procurement of the sources, which are extracted from First Sentry smoke detectors, for oversight at their handling at UT, for certification of the source strength and type, and for the shipping procedures outlined above.

Another aspect to be noted regarding radiation safety is replacement of muon monitor tubes in the alcoves. While the residual activation of all the tubes should be negligible, there will still be residual activity in the absorber cavern. Personnel replacing a failed tube in Alcove 0 will experience a dose of 20 mRem/hr if standing 1 foot from the absorber shielding after 1 week cooldown. Assuming the worst, and assuming that this 20 mRem is everywhere in the cavern, then personnel dose could reach 40 mRem to replace a tube (assuming 2 hours to do the job).

11 PEEK and Kapton

The components in the ion chamber tubes will make use of two plastics, PEEK and Kapton. The present section summarizes some of the available data on mechanical, electrical, outgassing, and radiation-hardness properties of these materials.

Kapton is a product of the Dupont Corporation which maintains a webpage on Kapton[6] and distributes documents of general specifications [9] and a summary of properties [10].

The typical form of Kapton used is the type HN film. It is a polyimide polymer made from the polycondensation of pyrometallic dianhydride and 4,4' diaminodiphenyl ether. The film is available in thicknesses of 0.0003" - 0.005" from DuPont and is assembled into various finished products by OEMs.

Kapton (as well as other polyimides) is commonly used in electrical applications where some degree of environmental resistence is necessary. It is able to work well at very high and low temperatures, is resistant to most any solvent, is nonflammable, and can absorb significant doses of radiation without degradation. Kapton can also be laminated and serve as a substrate for deposited circuits, making it ideal for electrical applications. When being used as a cable dielectric Kapton is typically applied to the conductor as a tape.

PEEK is a product of the Victrex Corporation[7] and is also known by the technical names of Poly (Ether Ether Ketone), Polyaryletherketone, or oxy-1.4-phenylene-oxy-1.4-phenylene-carbonyl-1.4-phenylene. PEEK belongs to the category of high performance thermoplasts.

PEEK has many of the same advantages as Kapton, but is more versatile as PEEK can be extruded, molded, machined precisely, or applied as a powder. PEEK is stiffer than Kapton and not available in films thinner than about .003", so is not as suitable for cabling. However, its superior flame retardance has made it useful as an outer jacket on electrical cabling. PEEK is not commonly used as a dielectric for coaxial cables.

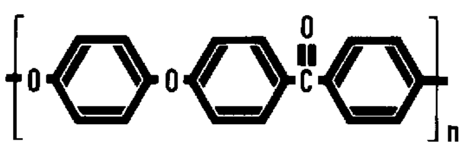

Figure 16: The chemical structure of PEEK [11].

The electrical properties of PEEK and Kapton are similar as enumerated in Table 2. The dielectric strengths are such that only a small thickness of either material is adequate in the nominal conditions of less than 1000 Volts.

The volume resistances of PEEK and Kapton are relatively stable at moderate temperatures. At 100° C Kapton's volume resistance decreases by about a factor of 3, and PEEK's decreases by about 20. At 200° C the difference is much greater with Kapton's decreasing to about 300 times below normal, and PEEK's is decreased by 7-8 orders of magnitude, suggesting that PEEK may be a poor high voltage dielectric above 200° C.

[6] www.dupont.com/kapton/

[7] www.victrex.com

	Kapton (25 μm film)	**PEEK**
Volume Resistivity (Ω·cm)	1.5×10^{17}	6.5×10^{16}
Surface Resistivity (Ω/square)	1.0×10^{16}	2.0×10^{16}
Dielectric Strength (kV/mm)	236	19

Table 2: Basic electrical properties of Kapton [9] and PEEK [11].

Some research has been done on the electrical properties of Kapton after radiation exposure, but not on PEEK. When exposed to 10^9 Rads of Co-60 γ radiation no degradation of dielectric strength was found, while the volume resistivity did decrease by a factor of 3. Kapton film was also tested with neutrons, but electrical properties were not considered [12]. As noted below the material became stiff and could be more easily broken.

PEEK and Kapton are both high-performance plastics that have significant strength (for plastics) and can survive in various conditions. Both resist most chemicals and can survive to very high temperatures.

Some of the basic mechanical data on Kapton and PEEK are listed in Table 3. The strength and modulus are typical of plastics. Victrex reports that PEEK maintains its mechanical properties until about 2 GRad where a "slight deterioration of flexural properties occurs" [11]. DuPont reports a 25% reduction in tensile strength after exposure to 1 GRad of γ radiation [10]. They also report that the film is darkened and tough after exposure to 10 GRad of thermal neutrons.

Kapton and PEEK are both useful at very high temperatures due to their stable chemical structures. Kapton undergoes a glass transition betweeen 360°C and 410°C, but has no melting point. Kapton remains solid until about 500°C and then oxidizes and is consumed around 650°C. If it is heated in a dry Helium environment it is not consumed at temperatures as high as 950°C [10]. PEEK undergoes a glass transition at 143°C and then melts at 340°C [11]. With large ionizing radiation exposure ($>$ 1 GRad) the melting point of PEEK decreases, and the temperature of its glass transition increases [13].

In addition to temperature resistance and mechanical strength, both materials are also impervious to most chemicals. Kapton has no know organic solvent, and PEEK resists most organic and inorganic solvents. Their resistance is weakened at higher temperatures ($>$ 200°C), and extended exposure ($>$ 1000 hours) can have an effect.

The outgassing properties of these materials are reasonably low. Kapton is commonly used in ultra-high vacuum applications and has a vapor pressure of $\sim 10^{-10}$ Torr, even under chamber baking conditions. A study by NASA [14] of the outgassing properties of various plastics lists kapton as one of the very best. NASA studied numerous materials out of concern for condensation by satellite materials onto optics on board the satellite. They quote the "%CVCM" (percentage of collected volatile condensed material) of various compounds. The

	Kapton (25 μm film)	**PEEK**
Ultimate Tensile Strength (MPa)	165	100
Tensile Modulus (GPa)	2.5	3.5

Table 3: Basic Mechanical properties of Kapton [9] and PEEK [11].

procedure of testing is to pump vacuum on the material for 24 hrs at 398 K, per American Society for Testing and Materials procedure ASTM E-595-90. For Kapton, the %CVCM is 0.01, making it lower than other well-known low-outgassers such as teflon. PEEK is not listed in the NASA manual, but is increasingly studied at Fermilab for use in the accelerator, so presumably it must also have a vapor pressure in the $10^{-6} - 10^{-8}$ range.

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