4.3 POWER SUPPLY SYSTEMS (WBS 1.1.3)

4.3.1. Introduction

The extraction/primary beam power supply system consists of the power supplies for the beamline elements, their local controls and regulation equipment, the cables and connections from the power supplies to the 480 VAC power panels and the cables and connections from the power supplies to the devices that they drive.

Table 4.3-1 summarizes the number and types of power supplies needed for the NuMI beamline. For beam tuning and focusing, each trim and quadrupole magnet has its own power supply. On the other hand the bend circuits use several 500 kW supplies in series (or for the V108 circuit a Main Ring Power Supply) in order to obtain the desired voltage levels. All power supplies are standard refurbished FNAL power supplies, with the exception of the kicker power supply and horn power supply. Some of the MI correction element power supplies will need to be built, but from a standard, existing FNAL design. The kicker and horn power supplies are designed and built specifically for the NuMI application. The horn power supply uses a transmission line to supply current to the two horns. The kicker power supply uses standard RG220 cable. The following sections describe the power supply system, starting with the conventional, mostly refurbished power supplies, then the kicker power supply and finally the horn power supply and its transmission line. Cables are covered briefly at the end.

Type	Number
Kicker Power Supply (requires a 60 kV charging power supply)	1
Horn Power Supply (requires 2 charging power supplies and a transmission line)	1
PEI 240 kW (horn power supply charging power supplies)	2
Main Ring Style	1
PEI 500 kW	10
PEI 20 kW	23
MI Correction element power supplies	19

Table 4.3-1 Summary of Number of Power Supplies and Types

4.3.2. System Description: Conventional Power Supplies

Table 4.3-2 through **Table 4.3-4** list the power supply circuits (except for the kicker), corresponding magnet types, numbers of magnets, their resistance, inductance, cabling information, current and voltage information, power supplies required and their corresponding voltages, currents and power. The two 240 kW power supplies used for charging the horn power supply capacitor bank are discussed in the section on the horn power supply. The others are discussed here.

Table 4.3-2 : Power Supplies in MI60

(See document TDH_V2_4.3_Tables_2-4.xls for tables 4.3-2 through 4.3-4)

Table 4.3-3: Power Supplies in MI62

Table 4.3-4: Power Supplies in Target Service Building

All the magnet supplies will be ramped. There will be seven high-current bend circuits: the kicker magnet (I:KPS6N), the first Lambertson magnet (I:LAM60), the second and third Lambertson magnets (I:LAM61), the C-magnet (E:V100) and three bend circuits (E:HV101, E:V108, E:V118). The power supplies are located in three areas, MI-60, MI-62 and MI-65. The extraction system power supplies (I:KPS6N, I:LAM60, I:LAM601, E:V100, E:HV101), the first 12 corrector element power supplies, and the first 6 quad power supplies are located in MI60. The second bend power supplies (E:V108), one 20 kW power supply (E:H104), and 6 quad power supplies are located in MI62. The final bend power supply (E:V118), one 20 kW power supply (E:H117), 9 quad power supplies and 9 corrector power supplies are located in MI-65.

The kicker power supply is covered in Section 4.3.3. The first Lambertson magnet, due to aperture restrictions in quad Q608 downstream of it, is run at a lower current than the last two Lambertson magnets. Thus there are two separate 500 KW power supplies for the three Lambertson magnets (I:LAM60, I:LAM61). The C-magnet is powered by a 500 kW supply (E:V100). The first bend string (E:HV101) consists of six EPB magnets powered by three 500 kW supplies in series. The second bend (E:V108) consists of six B2 magnets powered by a Main Ring type power supply. The circuit E:V118, the four B2 magnets, is powered by a four 500 kW supplies, run as 2 sets of 2 500kW supplies in series. There will also be 21 quadrupole circuits, each with a 20kW power supply and two dipole circuits, each with a 20kW power supply. There are nineteen low-current circuits for Main Injector corrector magnets. Several quadrupole circuits may be combined in the future to run from one power supply if it is shown to be an effective way to operate. The critical devices will be the E:HV101 and I:LAM61 circuits. Standard FNAL hardware is used for the critical device circuits.

4.3.2.1 Upgrades and Improvements to Conventional Power Supplies

All of the large NuMI power supplies (240kW, 500kW, Main Ring) and most of the smaller NuMI power supplies (20 kW and MI corrector power supplies) are re-used power supplies from decommissioned beamlines. The 20 kW and MI corrector power supplies did not need to be upgraded or refurbished. The others were re-furbished and upgraded to meet the anticipated 10-year lifetime of the NuMI beamline. The refurbishing included new voltage regulators, new gate firing circuits, water lines, and ramp calculators were installed. The power supplies were also modified for two-quadrant operation (invert) by removing diodes and adding silicon controlled rectifier switches (SCRs). Each circuit is set to use the maximum power supply voltage tap possible.

4.3.2.2 Power Supply Regulation

To meet the beamline specifications given in Section 4.1 particular concern needs to be given to the six bend supplies; the criteria are somewhat less stringent for quadrupoles and dipole correctors. There are three sources of current variation for magnet strings. One is the 720 Hz line ripple. The other two sources of current variation are line voltage changes and load changes. Simulations of a particular power supply (or series of power supplies) can be used to see the effects of these changes on the resulting flattop current. The present cost estimates for the NuMI beamline power supply regulation include costs for standard regulation plus the costs of a filter choke for three of the six magnet strings. An analysis of the power supply stability requirements for the new beam optics has been completed and is shown in **Table 4.3-5** through **Table 4.3-8**. Details are given in Section 4.1. A change request will be made to incorporate these requirements into the present cost and schedule. These beam stability criteria listed in Section 4.1, lead to the stability limits listed in **Table 4.3-5**, where instability in ppm is the plus or minus variation allowed in that loop relative to its operating current at flattop.

String	Maximum Current of PS	Peak Current (amps)	Corresponding target RMS in microns	Allowed Instability in ppm
Lam60	2500	916	160	900
Lam61	2500	1985	300	730
V100	5000	2692	200	670
HV101	2500	1670	20	100
V108	4250	4442	200	60
V118	5000	4173	200	70

Table 4.3-5: Power Supply Regulation Requirements due to Beam Stability

The power supplies also need to regulate well to minimize beam loss. The fractional losses at $4x10^{13}$ppp in the primary beam line should be kept below 10^{-4} in most locations and 10^{-6} in the central region of the carrier tunnel. MARS simulations of losses along the beamline are nearly complete. The results will be summarized in **Table 4.3-6**. One can clearly see that the requirements for power supply regulation to limit beam loss for groundwater activation are much less than those needed for beam stability and physics. (This is known from the data we have from the present study of beam loss using MARS and STRUCT.)

String	Maximum Current of PS	Peak Current (amps)	Corresponding Fractional Beam Loss	Allowed Instability in ppm	Allowed Instability Percentage Change
Lam60	2500	916			
Lam61	2500	1985			
V100	5000	2692			
HV101	2500	1670			
V108	4250	4442			
V118	5000	4173			

Table 4.3-6: Power Supply Regulation Requirements due to Beam Loss

4.3.2.3 Line Ripple

Filter chokes are used to filter out the 720Hz ripple on the line. When a PS current is changed, even if it is line-synched, it shifts slightly on the 720Hz ripple, which is quite sharply peaked. As a result, there is a fair amount of current variation despite line synching. Even extraction can vary by up to 30 microseconds. **Table 4.3-7** shows the current variation that would occur assuming no filter chokes, for each string. We will use filters on all the circuits listed **Table 4.3-7**. This requires 7 filters since the V119 string is two sets of 500 kW PEI's in series and thus requires two filters. One might argue that the Lam61 string does not need a filter, but the difference between allowable instability and the level without a filter is only a factor of 2. The requirement numbers were obtained by looking at single string variation, not multiple, thus we should err on the side of better regulation per string than the allowed instability ppm numbers show.

String	Maximum Current of PS	Peak Current (amps)	Allowed Instability in ppm	Variation due to 720 Hz in ppm with no Filters	Variation due to 720 Hz in ppm with Filters
Lam60	2500	916	900	1606	209
Lam61	2500	1985	730	349	17
V100	5000	2692	670	528	14
HV101	2500	1670	100	225	12
V108	4250	4442	60	202	4
V118	5000	4173	70	324	7

Table 4.3-7: Current Variation due to Line Ripple

4.3.2.4 Current Variation due to Line Voltage and Load Changes

Line voltage changes were simulated for the NuMI V108 string. Assuming a constant reference voltage, a 5% change in line voltage was easily corrected for at the level of 100 ma (at a flattop current of 4250 amps) by the standard voltage regulation loop of the power supply. This corresponds to ~24 ppm change. This level of line voltage change is the most one would expect and results in a current variation well below that required by NuMI. Thus standard regulation is sufficient for line voltage changes.

Load changes were similarly simulated for the NuMI V118 string. A 5% change in load resistance (corresponding to about a 10^{O} C change in the copper of the magnet, or the LCW changing 15^{0} C) resulted in a 1 amp change out of 4250 amps. This corresponds to a 240 ppm change. Other magnet strings have not been simulated, but would probably come to a similar result. **Table 4.3-8** shows the current variations due to load changes when using special FNAL electronics. Due to beam requirements and concerns about ease of bringing up the beam,, special FNAL electronics will be installed on circuits all 6 strings.

String	Maximum Current of PS	Peak Current (amps)	Allowed Instability in ppm	Variation due to Load Changes (ppm)	Variation due to Load Changes with FNAL Electronics (ppm)	Extra Factor Needed (regulation/spec)
Lam60	2500	916	900	653	326	0.36
Lam61	2500	1985	730	277	138	0.19
V100	5000	2692	670	287	144	0.21
HV101	2500	1670	100	304	152	1.52
V108	4250	4443	60	191	96	1.59
V118	5000	4173	70	240	120	1.72

Table 4.3-8: Current Variation due to Load Changes

4.3.2.5 Regulation Requirements

The conclusion is that filter chokes and FNAL electronics will be used for all 6 strings and either a BμLB or JITtER system will be installed for the three major bend strings (HV101, V108, V118). A BμLB system is more expensive and regulates throughout the ramp where as the JITtER system, under development in Beams Division, will sample and correct at the start of flat top. The JITtER system should be easier to support and less expensive and sufficient for NuMI, if the development shows it to be a reliable system.

Autotune will greatly help, but has its drawbacks as one must have beam and working beam position monitors to use Autotune. When beam first starts up, Autotune will not be able to correct things immediately. Thus we will use both Autotune and an additional level of power supply regulation. In addition, each string will be tuned for the maximum bandwidth. This is the standard way of starting up a power supply system.

The remaining types of power supplies in the primary beam line are 20 KW PEI's for the quadrupole magnets, 200 turn switchyard dipoles, and Main Injector (MI) trim power supplies. The 20kw PEIs have standard regulation of +/-0.05% of the maximum current of the power supply (100 or 200 amps). The MI trim magnets standard power supply regulation is +/-0.1% of the maximum current of the power supply (12 amps). We believe that this level of regulation is sufficient for the NuMI beamline.

4.3.2.6 Controls

The NuMI power supplies will have the same controls as the P1, P2, P3 and A1 lines. Operations will have only to adjust one point per load. The groups of supplies will be regulated by one current regulator, and thus will act as one. Each supply will have an SCR Unit with a closed voltage loop, the same as the single supplies. The supplies will all receive the same voltage reference. Each magnet load will have one current reference. We use C468 ramp generators, which are current referenced. We are installing a local DAC, which has better temperature drift numbers, in the current regulation system to improve the noise.

4.3.3. Extraction Kicker Power Supply

The requirements on the extraction kicker are similar to those of the long-batch kicker, which is operational at MI52. The normal operating mode will be one in which six Booster batches, each consisting of 82 x 18.9 nsec bunches, fill the Main Injector. The first Booster batch is sent to the antiproton source and the remaining five are extracted to NuMI. However, for periods when antiproton is not in a stacking mode it will be desirable to be able to extract six Booster batches to NuMI. Three kicker magnets are to be used in NuMI. The magnets are to be located in the region downstream of quadrupole Q602, with the power supply upstairs in the MI60 South Power Supply Room.

The kicker power supply will power two of the three magnets in series and then those in parallel with a third kicker magnet. The pulse-forming network (PFN) consists of two 32 section 10 ohm PFN's in parallel with one thyratron switch driving the magnets. A 60 kV power supply will be used to charge the PFN.

4.3.3.1 Specifications

The specifications for the kicker system are given in **Table 4.3-9**.

4.3.3.2 Thyraton

Figure 4.3-1 shows the NuMI thyratron enclosure. The CX1592C from Marconi Applied Technologies (née EEV) was selected for the thyratron, with thought of minimizing pre-fire rates. This is the same thyratron used for proton extraction for pbar production. A new triggering method, recommended by Marconi, will be used to give a longer thyratron life because of the longer length of the current pulse.

Kick Angle @ 120 GeV protons	900 µrad (3.6 kG-m), to radial inside of MI, nominal
Current Per Magnet	2460 A Nominal/ 2730 A Maximum
Nominal integrated field	3.6 kG – m (1.2 kG-m per magnet)
Maximum integrated field (110%)	4.0 kG-m
Field Rise Time (1%-99%):	1.30 µs
Field Fall Time:	N/A
Field Flattop Time:	9.78 µs minimum (6 batches)
Flattop During Pulse:	+/- 1%, best effort to +/- 0.5%
Flattop pulse to pulse:	+/- 0.5%
Maximum PFN Charge Voltage	60 kV
Maximum PFN Output Current	6000 A
Repetition Rate:	1.9 seconds
Maximum Charging Time:	1.5 seconds
Pulse Forming Network Length	11.5 µs minimum (=9.78 µs + 2 x 0.60 µs + 0.50 µs)
MI reset to transfer/next MI reset	1.25 seconds/1.83 seconds

Table 4.3-9: Specifications for the NuMI Kicker Power Supply

Figure 4.3-1: Thyratron Enclosure

4.3.3.3 Pulse Forming Network (PFN)

The design of the PFN must have a ripple period close to magnet transit time for best performance. The design of the PFN has to meet not only electrical constraints, but also physical size and cable routing constraints. The NuMI kicker power supply has two PFN's in parallel. Each PFN has 32 sections, 20 nF/section, 2.0 μH/section and a 49 kV nominal kick. The NuMI PFN also has increase coupling (12% vs. 2%) and longer lifetime capacitors versus the MI-52 design. **Figure 4.3-2** shows a schematic of the PFN design. **Figure 4.3-3** will show a simulation of the total integrated field. The simulation used as much detail as possible concerning the magnet and PFN. The purple line is for two magnets in series, the red line is for a single magnet. Once can see the rise time requirement of 130 nsec may be hard to meet with 6 Booster batches.

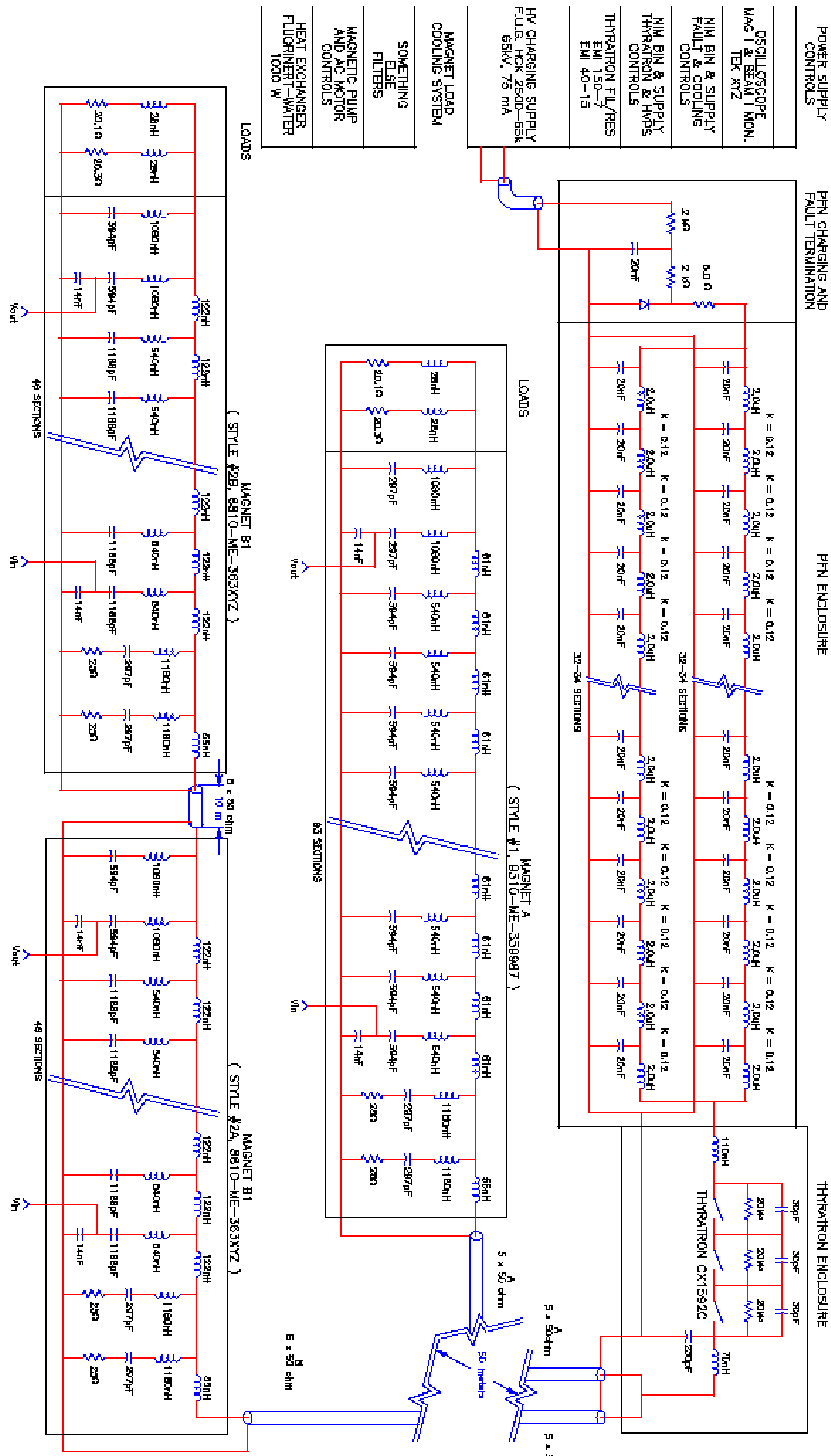


Figure 4.3-2: NuMI Kicker Design Schematic

Updated figure has not been made yet.

Figure 4.3-3: Simulated Kicker Integrated Field

4.3.3.4 Charging Power Supply

The charging power supply specification has been written. (ES-370-035), and needs to be reviewed.

4.3.3.5 Controls

The kicker will use a NIM bin based controls system. The modules are copies of the existing kicker controls for MI. Two special cables have been installed between MI-52 and MI-60 for fast inhibit & permit signals. **Table 4.3-10** shows the kicker fault signals that will be monitored.

Reset and if clears no problem	Investigate before resetting
Personnel Safety	HV Power Supply in Range (Absolute)
Trigger Supply Out of Limits	Magnet Current in Range (Absolute)
Filament Supply Out of Limits	Thyratron Prefire
Thyratron Oil Level Low	Thyratron No Fire
Thyratron Temperature High	Open Fault in Cable or Magnet or Loads
Magnet Fluorinert Level Low	(Magnet I)/(Charge V) Out of Limits
Magnet Load Temperature High	Shorting Fault in Cable or PFN or Loads
Magnet Load Fluorinert Flow Low	
Magnet Load Fluorinert Level Low	

Table 4.3-10: Kicker Fault Signals

4.3.4. Horn Power Supply

4.3.4.1 Horn Power Supply Specifications

The horn power supply must deliver 200 kA (average, ± 2.5%) pulses every 1.9 s. with a pulse-to-pulse repeatability of 1% and current monitoring to 0.4%. As a safety margin the power supply system will be designed to operate at up to 240kA. This results in a system load current of 7250 Arms operationally (8700 Arms design). The specifications are given in **Table 4.3-11**. The horn power supply system is located in the power supply room, underground, next to the Target Hall. The main components are the charging power supply, the capacitor bank, the silicon controlled rectifier (SCR) switches, the current transducers, and the safety system. The *NuMI Horn Power Supply Manual*, revised 4/02 is the most complete description of the horn power supply system.

Pulse width	2.6/5.2 ms
Bank Voltage	860/515 V
Pulse	1/2 sine
RMS current	5125/7250 A
Peak current	205 kA peak
Average flattop current	200 kA (average, ± 2.5%)
Pulse to pulse repeatability	1%
Current monitoring	0.4%
Repetition rate	1.87 seconds
Duty	continuous
di/dt, horn	268/146 A/us

Table 4.3-11: Power Supply System Output, operational level

In the horn power supply system, energy is stored in a capacitor bank and switched via a parallel array of SCR switches into the horn load. A parallel strip transmission line is used to connect the power supply to the horns. The circuit is a damped LC discharge circuit that will reach peak current when the SCR switch releases stored energy from the capacitor bank to the horns via the transmission line. The horn power supply can provide either a 2.6 msec or a 5.2 msec "flattop" pulse, depending on how the capacitors are connected. **Table 4.3-12** shows the design parameters for the horn power supply operating in these two modes. Also shown, for completeness, are the parameters for the prototype horn power supply used for testing horns at MI8.

	Prototype Horn Power Supply	Operational Horn Power Supply (5.2 msec)	Operational Horn Power Supply (2.6 msec)
Operational Current (kA)	200	205	205
Peak Possible Current (kA)	200	240	240
Peak Voltage (V)	800	550	1100
1/2 sine wave pulse base length	800-850 μsec	5.2 msec	2.6 msec
Repetition rate	0.5 Hz (up to 1.5 Hz)	0.5 Hz	0.5 Hz
Peak Current per capacitor	Varies	2 kA	4 kA
RMS current per capacitor	Varies	72.5 A	145 A
Total Capacitance		0.9 F	0.225 F
Comments	Current depends on the resistance of the circuit and the voltage limit of the PEI PS)	12 sets of 10 capacitors	Change 120 parallel caps divided into 12 cells to 60 series pairs; need two 240kw PEI's in series to get voltage (1100V)

Table 4.3-12 Design Parameters of Horn Power Supplies

4.3.4.2 Horn Power Supply Overall Design

The circuit used to provide current to the horns is a damped R-L-C discharge circuit as shown in **Figure 4.3-4.** It achieves peak current when the SCR (Silicon Controlled Rectifier) switch releases stored energy from the capacitor bank to the horns via the stripline. The load elements, listed in **Table 4.3-13**, are for the full-length stripline installation in the Target Hall and factor in skin effects and temperature rise. Power dissipation is given for the two possible pulse widths that can be generated.

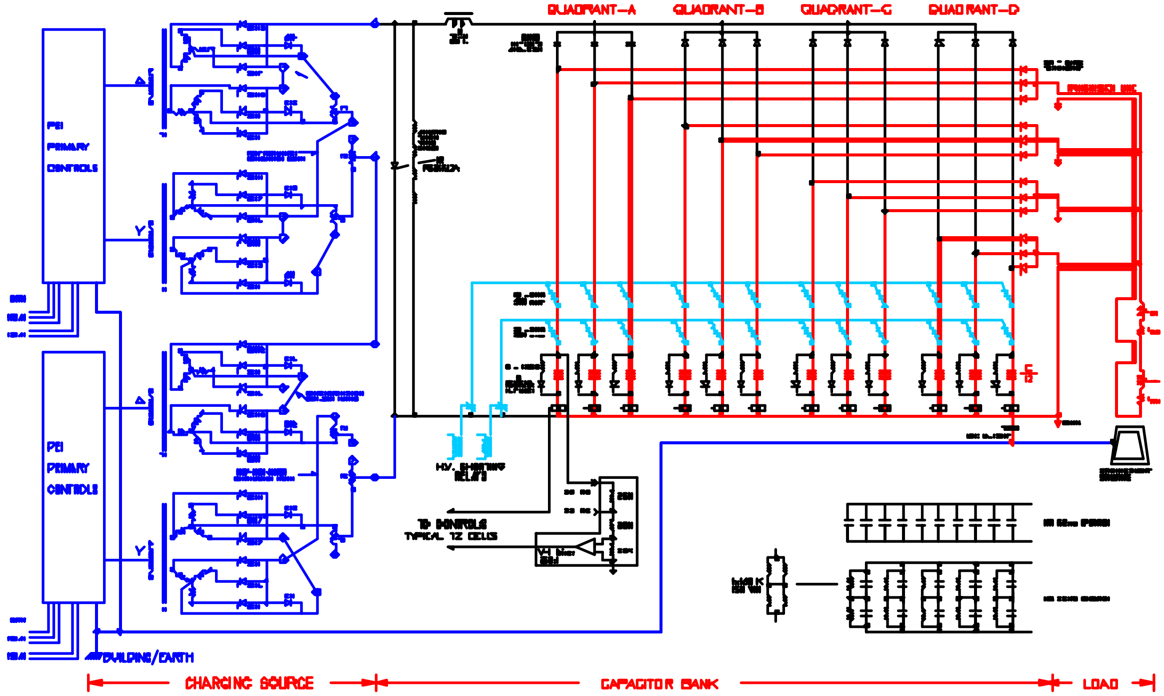


Figure 4.3-4 Horn Power Supply system schematic diagram.

Element	L, µH	R, mΩ	$P_{2.6}$ / $P_{5.2}$, kW
Horn #1	0.689	0.270	7.1/ 4.2
Horn #2	0.510	0.071	1.9/3.7
Transmission line:			
Transmission line: P. S. to beamline, 9.5 m.*	0.152	0.095	2.5/5.0
Transmission line: Between horns, 53.5 m.*	0.856	0.535	14.1/28.1
Cap. Bank, connections	0.1	0.050	1.3/2.6
Stripline connections*	0.1	0.010	0.26/0.52
Total	2.407	1.031	27.1/54.2

(*Estimate; from drawings, 7-Dec-01)

Table 4.3-13 Horn Power Supply Beamline Load Elements

Energy to provide the high current pulse for the NuMI horns is supplied by DC power sources (240 kW PEIs) that are used to charge the capacitor bank during the quiescent period between horn pulses. When the capacitor bank is configured to provide 2.6 ms pulse widths, the stored energy in the bank is 85 kJ. When configured for 5.2 ms pulse widths, the operating level of stored energy is 120 kJ.

With any array of capacitors connected in parallel, a capacitor experiencing a fault will have to absorb in addition to its own stored energy, the energy of all the capacitors connected in parallel with it and do so without case rupture. For this reason the capacitor bank is divided into twelve isolated sections, or cells, making the maximum amount of stored energy in any cell 12 kJ or less. All of the cells are isolated by diodes from each other and the charging source, and by SCRs from each other and the load. Consequently, the cells cannot communicate with each other under fault conditions. Having the capacitor cells isolated from each other forces current sharing among each of the twelve SCRs switching load (horn) current.

The style of case construction specified for these capacitors utilizes 14-gauge steel, instead of the normal 16 gauge, and have a fault energy containment rating of 25 kJ to provide a safety factor greater than two in each of the cells. The capacitor bank is assembled in four groups of three cells. Each group of three cells is referred to as a ‘quadrant.’ The quadrants are labeled “A” through “D.”

The bank normally operates with 120 capacitors in service, 30 in each quadrant. Provision was made to accommodate a maximum of 144 capacitors. All safety margins are determined for the maximum capability (240 kA design level) of the capacitor bank when used for NuMI beamline service. A basic schematic diagram of the high power elements is shown in **Figure 4.3-4**. FNAL drawing #9820-MD-370111 includes additional detail.

To minimize the voltage from the outer conductor of horn 1 to the target, located within the throat of horn 1 for the low energy beam, horn 1 is installed in the return side of the transmission line, nearest (electrically) to the capacitor bank. To achieve current flow in the proper direction, i.e. current in the center conductor of the horn in the same direction as the beam, it is necessary to make the positive side of the capacitor bank ‘ground.’ The capacitors in the bank are non-polarized and the PEIs can operate equally well with either terminal declared ‘ground’ since the PEI output floats.

The low-side bus from each capacitor cell (row) within each quadrant is connected to all of the others, and then connection to the enclosure frame is at a single point. All connections to an earth ground and the horn modules in the beamline installation are made to this point via the LEM® current monitor. The LEM provides for detection of fault currents in the grounding cables. The LEM signal output is tied into the controls interlock chain to terminate system operation in the event significant ground currents are detected.

Any electrical fault from the stripline or horns to the mounting structures or shielding steel in the beamline installation will allow the capacitor bank output current to return to the capacitors by a an alternate path, and ultimately through the cables connecting to the single point frame ground of the enclosure. The LEM current transducer will detect current in these cables.

4.3.4.3 Capacitor Bank Electrical Components

The capacitor bank specifications are given in **Table 4.3-14**. Based upon the inductance and resistance values provided for the two horns and the transmission line, the capacitance required for the bank is 0.90 Farads. The capacitor bank will be recharged by two of the standard Fermilab 240 kW power supplies. During operation of the horns the calculated power consumption is 83 kW. The required voltage for operation is 515 volts. To avoid creating transients on the power line a 1 mH inductance will be inserted between the power supply and the capacitor bank. The design uses 120 parallel capacitor units (7.5mF, 670V) divided into 12 cells, 10 units per cell and two empty slots per cell in case more capacitance is needed to make up for less than expected inductance for the target hall circuit. This design provides the 5.2 msec pulse. To obtain the 2.6 msec (half pulse), the 120 pairs in parallel are switched to 60 series pairs (with each pair being 3.75uF, 1340 V) in parallel. This yields a total capacitance of 0.225F or 1/4 the full pulse design amount. The 2.6 msec operational setup requires two 240 kW PEIs to run in series to obtain the 1100 volts needed for operation. This has been done before at Fermilab. The pulse waveform is given in **Figure 4.3-5**.

Peak current, maximum	240 kA (Design Rating; 120%)
Peak current, operating	205 kA
RMS current	8700 A (Design Rating; 120%)
Capacitance/unit	7,500 +/- 5% uF
Number of cells	12
Installed capacitors/cell	10
Total No. Caps installed	120
Max. No. capacitors/cell	12
Maximum No. capacitors	144
Capacitance/cell	18.75 mF / 75 mF
Installed Capacitance	0.9 Farad
Max. capacitance	1.08 Farad
Capacitor voltage rating	670 $V_{Working}$ /1340 $V_{Hi\text{-}pot}$
Switching element	SCR array, 12 parallel devices
SCR Mfg, Part Number	Eupec, Inc., T2710N20TOF

Table 4.3-14: Capacitor Bank Specifications

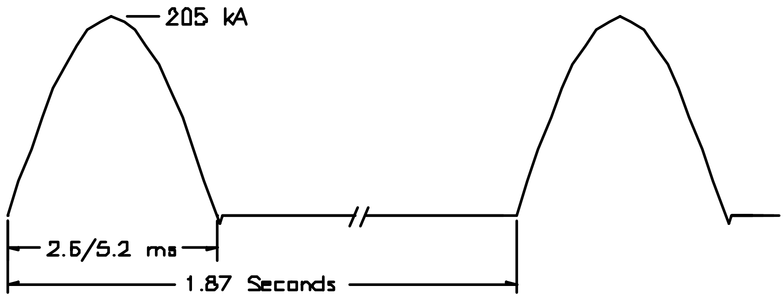


Figure 4.3-5: Capacitor Bank Pulse Train Waveform

We have chosen the metalized polypropylene construction for the capacitors specifically because they fail gracefully, or experience soft failures. They are fitted with pressure switches to detect any pressure build-up co-incident with soft failures and these switches will be tied into the interlock system of the controls. We have specified a capacitor case containment rating of 25 kilo-Joules when the maximum operating energy in any one cell is 15.7kJ. The nominal operating energy in each cell is 10.6 kJ. The absolute max energy available, assuming the PEI goes to full it's full output of 800 volts, is 22.4 kJ per cell. All of the cells are isolated from each other by semi-conductors, SCRs or diodes.

Capacitor Row Buses

The capacitor row bus extension tabs are constructed of 0.063" copper sheet stock with tab extensions to the respective positive and negative bushings of every second capacitor in the row. This every-other-one arrangement allows the free terminals of the capacitor pairs to be connected in a series, or parallel arrangement depending on the pulse width desired. For 2.6 msec operation the parallel arrangement is used.

Silicon Controlled Rectifier (SCR) Modules

The SCRs used in the capacitor bank to switch stored energy from the capacitors are assembled into modular sub-assemblies. Twelve assemblies, one for each capacitor row, are used in the capacitor bank. The assembly includes two water-cooled heat sinks, an SCR, bus bar terminals, and a compression clamp to hold the SCR under 10,000 lb. pressure. The modular approach is instituted to allow quick change-out in the event of an SCR failure. A snubber network is installed across each output SCR to protect it from voltage transients. The combination of a 1 uF capacitor in series with two parallel-connected non-inductive resistors is used. The respective snubber circuits are mounted adjacent to each SCR. **Table 4.3-15** shows the SCR ratings.

V_{DSM}, V_{RSM}	2,200, 2,300 V
I_{av}	3,700 A
I_{rms}	5,800 A
I_{tsm}	54,000 A

Table 4.3-15: SCR Ratings

Firing Circuits

Firing circuits provide the signal to the respective SCR gate terminals that initiate conduction of the devices. The firing circuits used to trigger the output SCRs are adapted from the Fermilab Low Beta Power Supply system. Circuit modifications are incorporated to increase the trigger pulse current amplitude to 6 Amps during the initial microsecond, decaying in several additional microseconds to 1 Amp for the remainder of the pulse. These modifications are documented by FNAL drawing # 9820-EC-370116. Each of the 12 output SCRs in the capacitor bank has a dedicated firing circuit. Three identical circuits are included on a single printed circuit board. Four printed circuit boards are installed, one for each quadrant of the capacitor bank. The over-all pulse width of the gate signal for the SCRs is controlled by the electronics in the Trigger Fan-out Box and must be adjusted such that the pulse width does not exceed the on time of the SCRs.

The output SCRs of the capacitor bank float at the operating voltage of the system. The firing circuit board components provide 1,500 Vdc isolation between the low-level input pulse and the 120 Vac power, and the output pulse to the SCRs. Consequently, the majority of the components on the circuit board and the co-axial cables carrying the trigger pulse to each SCR float at high voltage as well. The co-axial cable outer jacket is not rated, with respect to ground, for the potentials the system may be operating at. Subsequently, the gate pulse co-axial cables are dressed away from structures at ground potential, or double insulated in areas where structures are unavoidable. Red colored RG-58 co-ax cable was installed to signify the application is operating at high voltage.

Trigger Fan-out Box

The trigger fan-out box is mounted to the ceiling of the enclosure, above the ‘C’ quadrant capacitor structure. It receives the ‘SCR Trigger’ pulse from the controls via fiber optic cable. A second fiber optic cable carries a ‘status’ signal back to the controls to verify that the trigger fan-out circuit has all of the appropriate voltages present. The status information is included in the interlock chain and must be present for system operation

Four parallel outputs from this circuitry are connected to the respective SCR firing-circuit pc-board of each quadrant. Two additional ‘sync pulse’ outputs are generated within and are available externally at the connector feed-thru panel, located above quadrant ‘C.’ The two sync signals are 1-μs in width, TTL level, buffered and synchronous with the trigger for the capacitor bank output SCRs.

Voltage Dividers

A voltage divider is installed in each of the capacitor cells (rows) to monitor the performance of the respective cells. The control electronics monitors these signals on a continuous basis throughout the operating cycle, looking for any imbalance. The frequency compensated voltage divider circuitry includes a voltage to current converter with a low impedance output. This approach was implemented for improved noise immunity and the ability to drive long signal lines to the control electronics.

Output Current Transformers

A passive current transformer (CT) is installed in the low-side bus of each capacitor row. Its output is 1 volt/kA and appears as a voltage source with 50 ohms in series. The twelve individual signals, one from each CT, pass through the connector panel located above quadrant C of the enclosure. The 50 ohm input impedance of each channel of the control electronics provides termination for the current transformers.

Reverse Energy Discharge Resistor and Diode

Energy reflected from the load inductance will be stored in the capacitor bank, but have the opposite polarity. Because of the relatively large amount of resistance in the stripline and horns the amount of energy reflected is approximately 1.5 kJ (15%), to low to have made the additional components necessary for energy recovery circuitry economically worthwhile. Consequently, the reverse energy is dissipated in a resistor switched into the circuit by a freewheeling diode. The resistor-diode combination is connected in anti-parallel across each capacitor cell. The diode for each cell is mounted as a water-cooled assembly to the capacitor low-side bus, adjacent to the current transformers.

Humidity Sensor

A humidity sensor is installed within the capacitor bank enclosure on the ceiling of "C" quadrant. It was included in the equipment to monitor enclosure humidity. It has a measuring range of 0-100% and an accuracy at 20˚C of; +/- 2% from 0 – 90% RH, +/-3% from 90 – 100% RH. Temperature dependence: +/- 0.02 ˚C /˚C. It operates on +5 Vdc and has an output of 0 –1 V with respect to common for 0 – 100 % RH indication. Connection to it is via a dedicated connector on the enclosure feed-thru panel.

4.3.4.4 Charging Power Supply Design Issues

Two 240 kW PEI power supplies are used for charging the capacitor bank. Their specifications are given in **Table 4.3-16**. These PEI power supplies used for the capacitor bank were originally designed for powering magnets under constant current or programmed functions. When used for charging capacitors, the charging current will go to zero once the capacitors have achieved the desired voltage, confusing the power supply regulator. As an aid to voltage regulation, a resistor is installed across the PEI output to pull a small amount of current at all times. The resistor is constructed of four series connected, water-cooled elements as used in domestic electric water heaters. Their combined series resistance of the four elements is 138 Ohms. These resistors are mounted within the capacitor bank.

PEI (Power Energy Industries)	240 kW
Maximum output voltage, Volts	200/400/800
Maximum output current, Amps	1200/600/300
Voltage regulation	0.1 %
Current regulation	0.05 %

Table 4.3-16: Charging Power Supply Specifications

A 10 mH inductor is connected between the PEI charging source (supply) and the capacitor bank. Its purpose is to limit undershoot current that occurs as a result of reverse recovered charge on the capacitor bank at the end of each discharge pulse. Design specifications of the choke are provided in FNAL Specification # 9820-ES-370036.

A by-pass diode is located within the capacitor bank enclosure, adjacent to the choke. This single diode appears electrically across the multiple series by-pass diodes of the PEIs and is meant to carry all of the remaining undershoot current, diverting it around the PEIs. Its anode is connected to the input end of the choke (PEI negative connection) and its cathode to ground (PEI positive connection).

Diodes are installed between the capacitor bank side (electrical) of the charging choke and each capacitor cell of the bank. Their purpose is two-fold. First, they provide isolation of the PEIs to prevent the delivery of stored energy from the capacitor bank into any fault that may occur in the charging supplies. Their second purpose is to provide isolation from cell to cell, preventing stored energy delivery into a faulted cell from the remainder of the capacitor bank. The diodes are of modular construction and are installed in sets of three on water-cooled heat sinks. The assemblies are located between the capacitor support structure and the G-10 SCR panel, in each quadrant, near the floor of the enclosure.

4.3.4.5 Electrical Safety

Bleeder Resistor P.C. Board

When the capacitor bank is configured with series pairs (2.6 or 5.2?msec) of capacitors, bleeder resistor boards must be installed as a safety measure. The low side terminal of all series pairs is grounded via the high current bus in each capacitor row. The high side terminal of the pair will be grounded when the LOTO procedure is carried out to completion. The mid-point between the capacitors, however, is not grounded and could retain a charge relative to ground. The installation of the bleeder resistors (100 kOhm) will provide a leakage path to effect discharge of any remaining stored energy after the system is shut down. Additionally, bleeder resistors will prevent any accumulation of stored charge from incidental energy sources. The resistance value is high to keep power loss in the aggregate of the bleeder networks to an acceptable level. Redundancy for safety is established on each PC board by the use of four resistor elements connected in a bridge configuration, two in series by two in parallel with the mid point of the series resistors connect together. Hence, two resistors must fail before the bleeder network becomes inoperative.

The time required to achieve full discharge is equal to five R-C time constants (63 minutes). The bleeder resistors are not to be relied upon to discharge the capacitor bank for maintenance purposes. LOTO procedures must be followed before any maintenance is to be performed within the capacitor bank enclosure or the PEI power supplies.

Energy Dump Resistors and Shorting Relays

A separate dump resistor is installed for each capacitor cell and is connected to a common shorting (grounding) relay, maintaining the cell-to-cell isolation necessary for safety. A second identical set of resistors and shorting relay is also installed to provide redundancy. These resistors are air-cooled and rated to absorb 27 kJ each, sufficient for the maximum stored energy of system operation with greater than a factor of two safety margin. When system shutdown occurs during a charge cycle, or an interlock interrupts normal cycling, energy stored in the capacitors will be switched by the shorting relay into the dump resistors where it will be safely dissipated.

Ground-sticks

A pair of ground-sticks is provided on each side of the capacitor bank enclosure, secured to the inside of one of the center bay doors. One of the pair includes a resistor assembly that will limit potential discharge current to a safe level. The 'hard-ground' stick does not use resistors. The two ground-sticks are inserted into the retaining mounts on the center bay door of one side of the enclosure. The storage points on the doors are equipped with interlock switches to assure the system is not energized while a ground-stick may be applied to the capacitor bank circuitry. When the ground-sticks are stowed it is essential they be fully seated in the holders in order to make-up the interlocks.

4.3.4.6 Controls

General Description

The control system was established as a joint development effort between the NuMI and MiniBoone projects since the two systems are similar in most requirements. Some functions required by the MiniBoone system are not used for NuMI. Hence, some LEDs are not illuminated during normal operation when in use for the NUMI horn system. The controls system consists of five plug-in modules in a rack-mounted frame. Two modules of the same model are used to monitor current and voltage balance in the capacitor bank, however they are not interchangeable due to different calibrations for the respective functions. A separate chassis mounted just below the controls chassis provides DC power for the control modules.

Monitored system parameters:

1. Output current of each cell to 0.4 % or better
2. Current in each transmission line pair
3. Current imbalance between stripline pairs
4. Total output current
5. Capacitor voltage in each cell
6. Capacitor bank over voltage and over current
7. PEI over current
8. Ground faults
9. Over temperature conditions of horns
10. Coolant flow loss to horns, PEIs, capacitor bank
11. Capacitor over-pressure
12. Equipment entry

The local resident power supply controller, beside permitting local operation of the equipment separate from control-room operators, is to monitor all of the operating parameters watching for of limit conditions and safely shutting the system down when such condition are detected. All safety related interlocks would be by hardware. We do not depend on software of personnel safety. There is no other solid-state device that even comes close to the switching capability and ruggedness of SCRs. It has be recognized that the very nature of SCRs is that once triggered there is no way to turn them off other than there being an occurrence of a subsequent 'current zero. We will, however, detect any and every fault in the equipment and turn it off to prevent a second pulse.

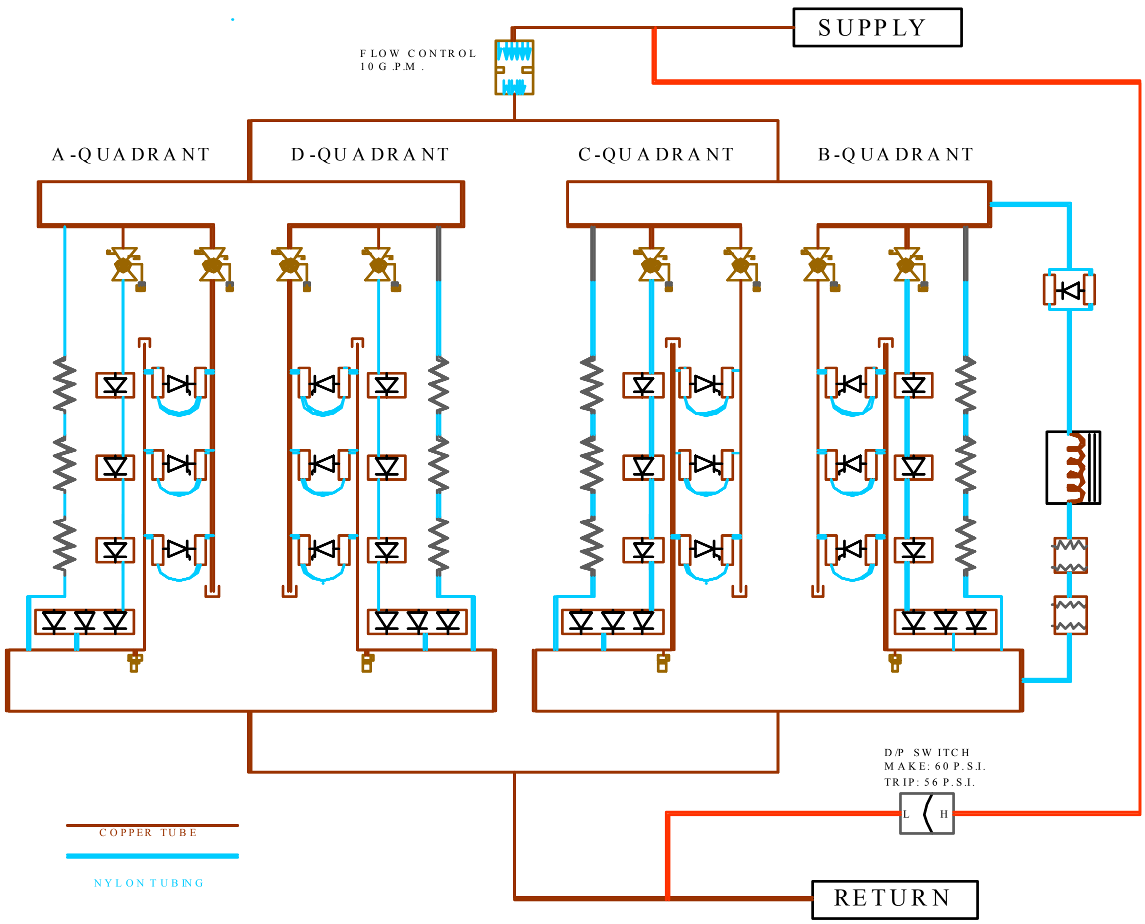
4.3.4.7 Cooling System

Figure 4.3-6 shows the capacitor bank water system schematic. With two exceptions, all the heat generating components, resistors, charging choke, diodes and SCRs associated with the capacitor bank in the enclosure, are cooled directly by water. The first exception is the capacitor energy dump resistors, which operate only momentarily when the system is turned off or the interlock system interrupts normal operation. Consequently, a negligible amount of additional heat is dissipated within the enclosure from these resistors. The second exception is the stripline. It is convection cooled and releases its heat to the air within the enclosure. A cooling water supply temperature of 95˚F, contributing some heat to the enclosure, plus the heat given off by the stripline serve to keep the enclosure internal temperature well above the ambient dew point during operation. This heat is conducted through the capacitor bank enclosure walls and radiated to the exterior environment.

Water Flow, typical:

Capacitor bank	9 gpm @ 80 psi differential
PEI, each	6 gpm @ 80 psi differential
Δp Switch setting	60 psi, PEIs and Cap.Bank, each

Water is carried either by copper pipe or Nylo-Seal® nylon tubing. Nylo-Seal has a working pressure rating of 400 psi., and a burst pressure rating of 1200 psi. Swagelok and Parker fittings are used throughout for the plastic tubing. Flow balancing valves are installed internal to the enclosure to establish the flow rate to the various parallel water paths. A self-regulating flow control valve controls the total water flow rate for the capacitor bank. The 10-gpm device is



installed in the supply side water line.

Figure 4.3-6: Capacitor bank water system schematic. (See Drawing #9820-MC-370054 for complete information and symbol key.)

4.3.4.8 Mechanical Design

Enclosure

The enclosure is constructed to Fermilab specifications per FNAL drawing number 2782.000-ME-314551. It measures 75" high x 210" long x 69" wide. We have specified a cabinet constructed of 14 Ga. steel to offer an added layer of personnel protection. It is constructed of mild steel and built in three sections; a center section housing the SCR switch assembly, and the two identical capacitor bank sections, one on either side of the center unit. All are constructed as a floor pan and a roof pan, separated vertically by mullions that form the corners and supports for the enclosure doors. The sections have mating flanges secured by multiple bolts to make up the complete enclosure. In the area adjacent to each flange bolt the steel has been left un-painted and silver-plated by the enclosure vendor. The plated areas were coated with moisture excluding grease prior to assembly to preserve optimum electrical contact between the enclosure sections. All sides of the enclosure are equipped with doors to allow full access to internal components. The door mullions in front of the capacitors in each quadrant are removable to facilitate capacitor replacement. **Table 4.3-17** lists the enclosure mechanical parameters.

Length	209 inches, (5.31 m), without doors installed
Width	70 inches, (1.78 m), without doors installed
Height	79 inches, (2 m), [81" including C-channel]
Weight	22,000 lbs., (10,000 kg)

Table 4.3-17: Enclosure Mechanical Parameters

All doors are readily removable, with the exception of the two doors on the end of the enclosure adjacent to the output stripline. By necessity those two doors have been modified to slide on tracks, rather than swing, and are not easily removed.

Oil containment

The most likely capacitor failure mode, in terms of oil leakage, is the loss of seal under one or more bushings. Placing capacitors with their bushings "up" would be the preferred orientation, negating any leakage concerns. However, to facilitate removal and replacement and to permit a compact design that could be lowered as an assembled and tested unit into the underground cavern, the capacitors are mounted horizontally with their bushings toward the outside of the enclosure. The two-inch lip-height of the floor pans in the capacitor sections of the enclosure provides 14 gallons of potential oil containment in the event of capacitor leakage. The capacitors used in the capacitor bank are impregnated with rapeseed (Canola) oil, a biodegradable vegetable oil. Each capacitor contains approximately 2.5 gallons of oil. Therefore, as many as 5 units in either enclosure end-section could spill their entire contents without exceeding the oil containment capacity for that section.

All penetrations in the enclosure floor pans have been sealed or curbed to prevent leakage to the outside. With any capacitor losing oil, it is likely that electrical failure of the capacitor will follow at some point. Any capacitor electrical failure will contribute to a current imbalance of the capacitor bank output and eventually be detected by the local controls, resulting in shutdown of the power supply system.

Capacitor Support Structure

The capacitors constitute 50% of the total weight of the enclosure assembly. During transport the structures supporting the capacitors in each quadrant are lifted directly via the four hoist rings on top of the enclosure. Each hoist ring is rated for 10,000 lbs vertical lift capacity. Internal and external structural members cross brace the capacitor supports to allow transport of the capacitor bank as a single unit. The balance of the weight of the components within the enclosure is carried through the enclosure structure to the capacitor supports. The 1" thick G-10 panels that mount the switching SCRs in each quadrant also serve as torsional webs to give the enclosure torsional stiffness.

Ground-cable Penetration

Ground cables connecting the capacitor bank low-side terminal to the horn modules, via the LEM, for ground fault detection exit the enclosure through a curbed hole in the base of the enclosure on the output stripline end. The purpose of this curb is to maintain the oil containment capability of the enclosure floor pan. The cable opening is sufficiently large to allow for the installation of two 900-mcm-ground cables with some room to spare. The excess opening should be sealed off after the installation in the underground power supply room to prevent the entrance of vermin.

4.3.5. Transmission Line

4.3.5.1 Overall Design and Specifications

A parallel strip transmission line is used to connect the power supply to the horns. The circuit is a damped LC discharge circuit that reaches peak current when the SCR switch releases stored energy from the capacitor bank to the horns via the transmission line. A transmission line consisting of a four-layer assembly of two parallel plates is necessary to connect the output of the power supply system to the horns. **Figure 4.3-7** and **Figure 4.3-8** show the layout and dimensions of the transmission line. In **Figure 4.3-8** the upper portion of figure shows the stripline cross section at a typical joint, held at 28,000 lbs by the spring style bar clamp. The lower portion of figure illustrates the mid-line style of aluminum bar clamp. An insulator separates each pair of aluminum alloy bus conductors. Aluminum spacers separate adjacent pairs. Inside the Target Hall beamline shield the insulation is a 1cm air gap with TS ceramic spacers. Outside the shield, Kapton polyimide insulation of 0.5 mm total thickness is used. The completed assembly is held in compression by ceramic sleeved through bolts at the spacer locations and compression clamps in the region where Kapton is used (if it is used). This configuration yields an equivalent transmission line width of 1.2 meters in a compact cross section. **Table 4.3-18** lists estimated transmission line dimensions and parameters.

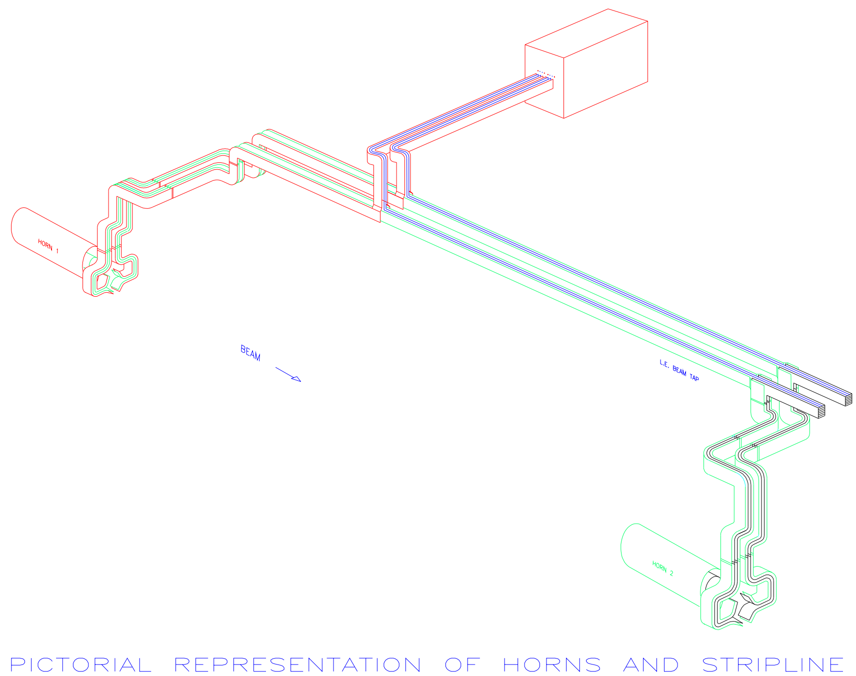


Figure 4.3-7: Stripline Pictorial Representation

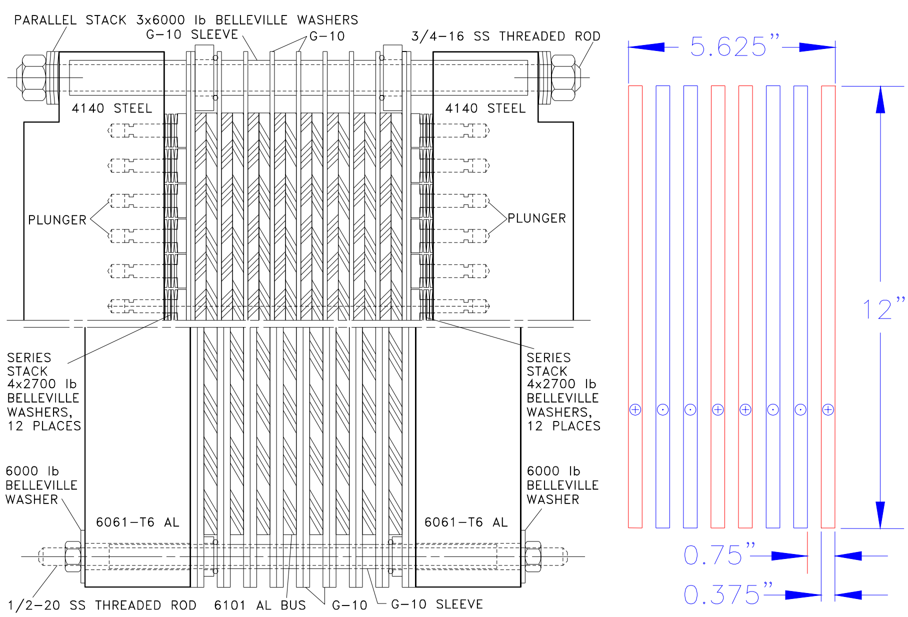


Figure 4.3-8: Stripline Drawing and Pictorial Cross Section.

The transmission line must deliver 200 kA (average, ± 2.5%) pulses every 1.9 seconds to the horn. As a safety margin the power supply system, including the transmission line, is designed to operate at up to 240kA. This results in a system load current of 7250 A_{rms} operationally (8700 A_{rms} design). The estimated circuit parameters were listed in **Table 4.3-13**. These calculated load values include effects of DC resistance, skin effect, temperature, transmission line conductor cross section and spacing.

Conductor material	6101-T61 Aluminum alloy
Conductor width	12 inches, (30.5 cm)
Conductor width at horn joints	8 inches, (20.3 cm)
Conductor thickness	0.375 inches, (0.953 cm)
Conductor spacing	0.375 inches, (0.953 cm)
No. parallel pairs	4
Inductance @ 100Hz	4.9 nH/ft., 16 nH/m of length
Resistance @ 100Hz	3.05 uΩ/ft., 10 uΩ/m of length
Power loss, 2.6 mS	80 W/ft., 260 W/m of length
Power loss, 5.2 mS	160W/ft., 530 W/m of length

Table 4.3-18: Transmission Line Parameters

The transmission line is a 12,000 lb. structure and thus its support is non-trivial. The transmission line is in approximately 20’ long sections. Transmission line joints are to be welded except where connection/disconnection is needed. One piece of the transmission line runs across from the Target Hall to the horn power supply room (see **Figure 4.3-9**). The second long piece of the transmission line runs along the Target Enclosure to the horns. Disconnects/connects are will be located in the horn power supply room, in the Target Hall where the transmission line emerges from the penetration, above the shielding at each horn and inside the shielding at each horn.

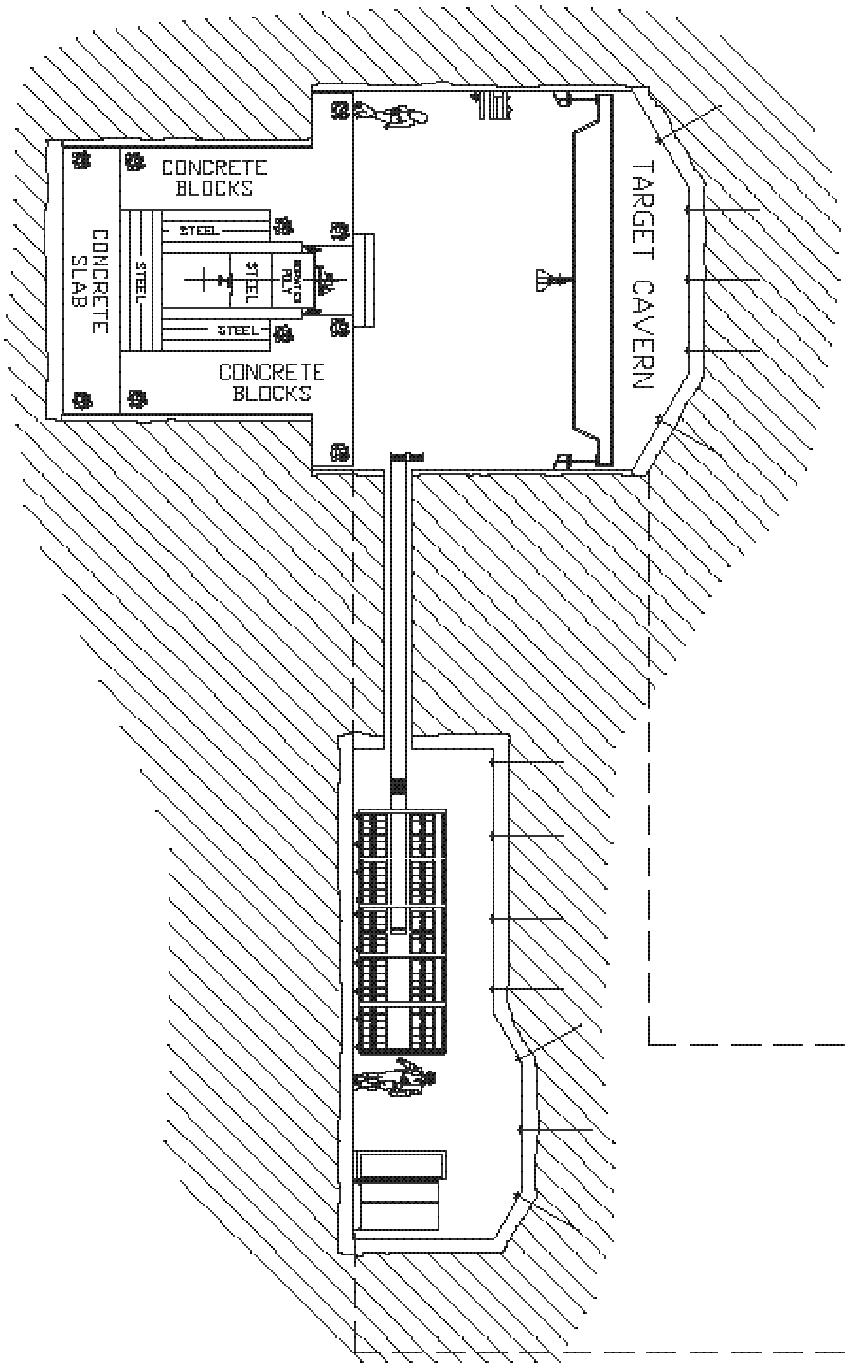


Figure 4.3-9: Target Hall and Power Supply Room Cross Section Conceptual Drawing

Transmission Line Cooling:
The target chase is cooled by 28,000 cfm flowing in the beam direction in the horn region. The beam heating in this region is less than 183 KW/m^3. The electrical heating is estimated at ~27 KW/m^3. For the stripline between the remote disconnect clamp block and the horn, the air flow through the target pile for the target pile cooling provides satisfactory cooling of the stripling to

remove the energy deposited from beam heating and from i^2r losses. The thermal analysis results are shown in **Figure 4.3-10**. The highest temperatures seen are 88°C at 4E13 ppp.

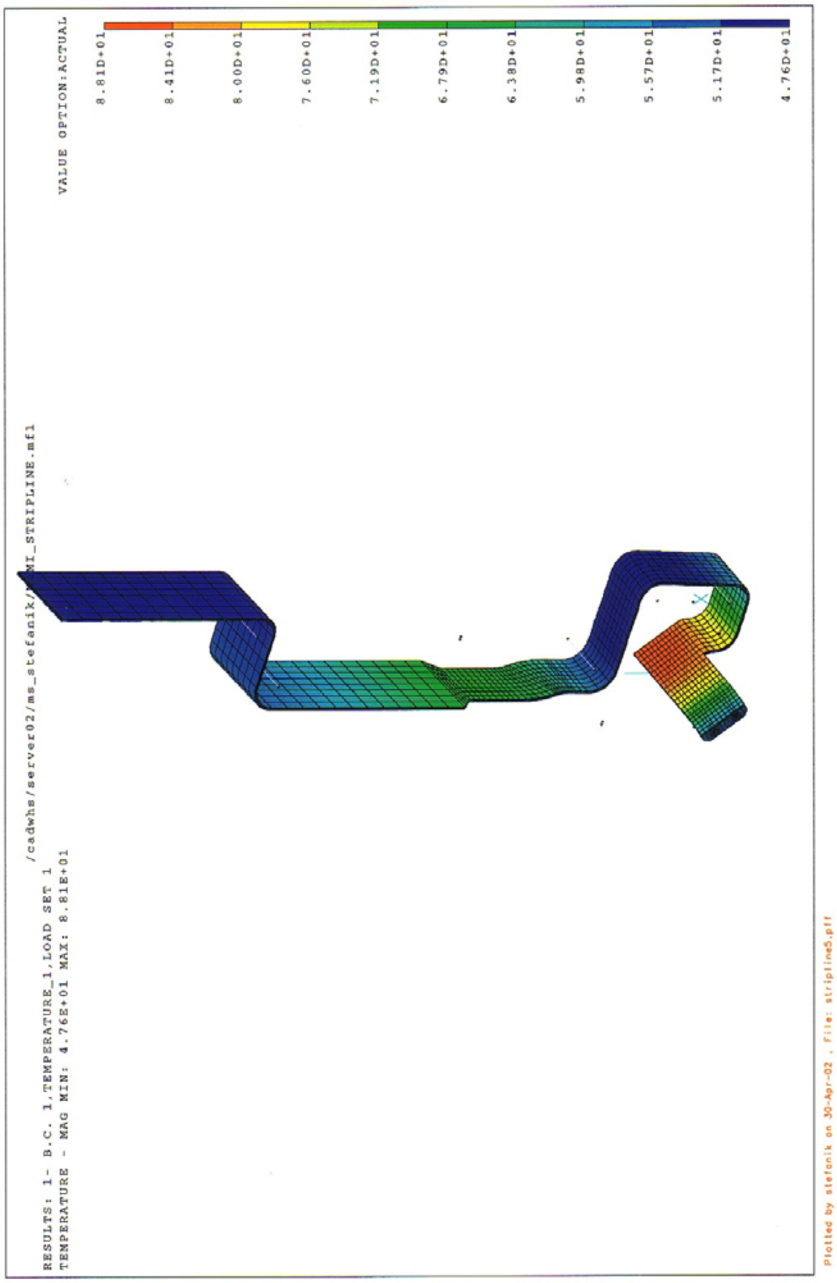


Figure 4.3-10: Transmission Line Beam Heating with AirFlow, Horn 1 Region

4.3.5.2 Transmission Line Joints

The transmission line joint, where the transmission line connects to the horns, is a complicated region. **Figure 4.3-11** and **Figure 4.3-12** show the plan and elevation view for the design in the area. The eight strips of the transmission line must connect to the bell shape of the horn. For horn 1, some amount of movement (+/- 3 mm horizontally and/or vertically) is desired also.

This area will become highly radioactive and thus the desire is to have the joints last as least as long as the horns do. Add to this that they will be pulsed every 1.9 seconds with 200 kA, which causes some amount of vibration and one can see the difficult issues with this area of the design.

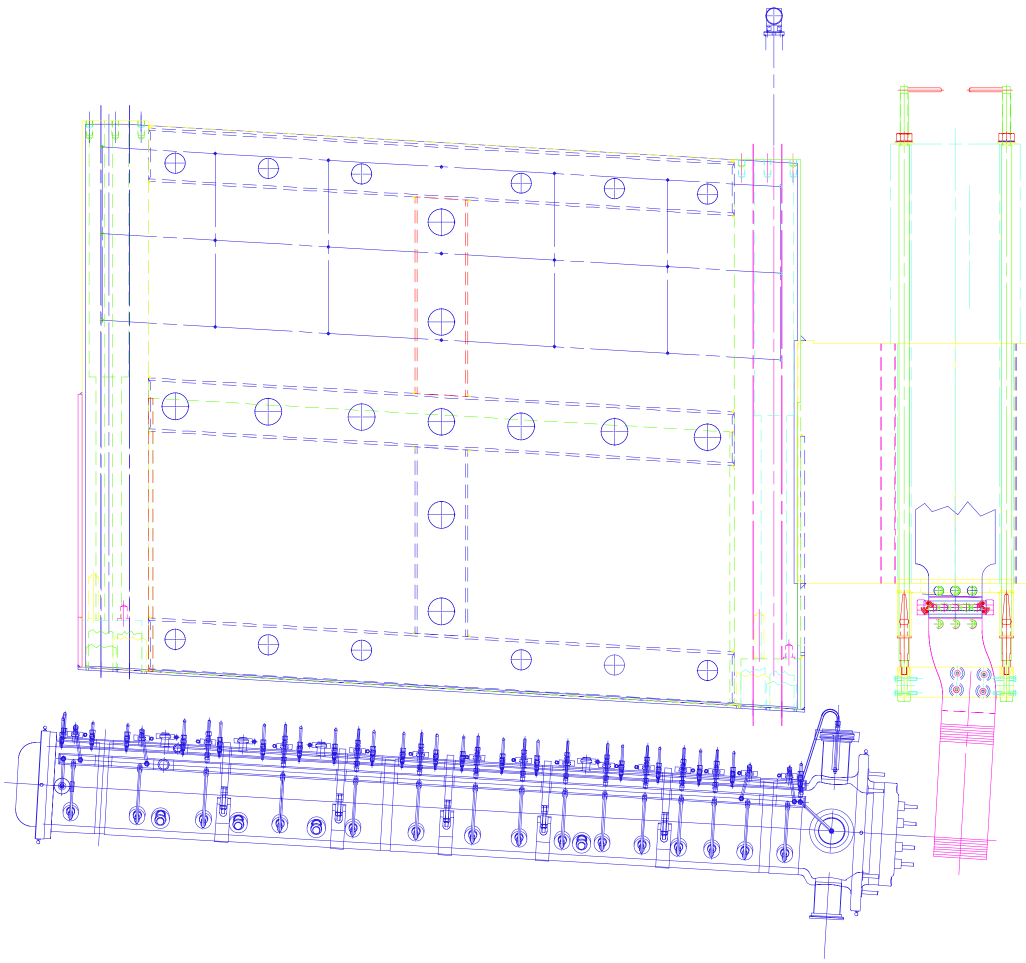


Figure 4.3-11: Horn, Remote Clamp and Transmission Line Elevation View

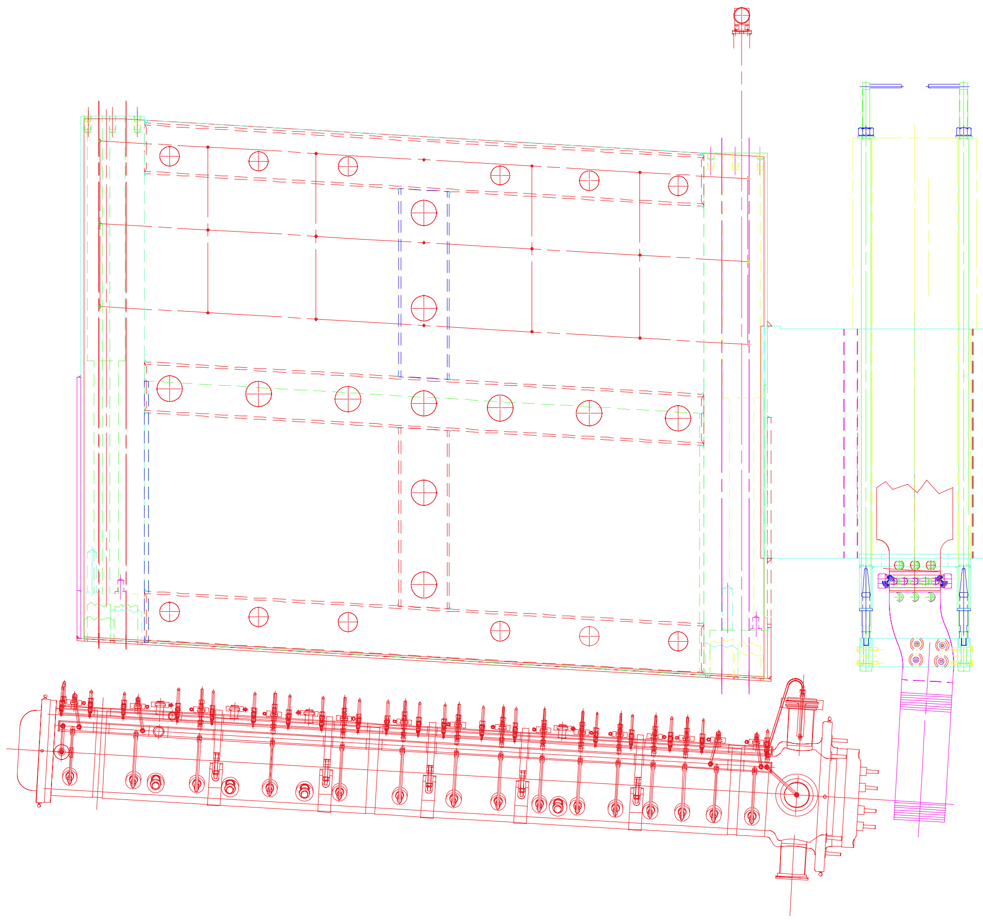


Figure 4.3-12: Horn, Remote Clamp and Transmission Line Cross Section

Fatigue Lifetime:

The part of transmission line connected to horn, the joint, will be replaced each time a horn is replaced. The horns are designed to last at least 10 million pulses. Thus the joints are designed to last 10 million pulses also. The horn fatigue lifetime safety factor for 10 million pulses is about 3.5. The maximum force desired on the horn upon displacing horn 1, is ~ 400 lbs. A fatigue lifetime safety factor similar to that of horn 1 is desired with this design. ANSYS analyses have been completed on the horn 1 joint design, using the appropriate thermal loads (88^{o}C), magnetic loads, and the maximal (3mm) offsets. They indicate a fatigue lifetime safety factor at least as large as that for the horns.

The horn 2 joint is based on the same design as the horn 1 joint, but scaled up to horn 2 dimensions. ANSYS results show that it is flexible enough to accommodate the expansion of horn 2. Horn 2 expands 0.033 cm and the ANSYS results show a maximum force of ~ 50 lbs on the horn.

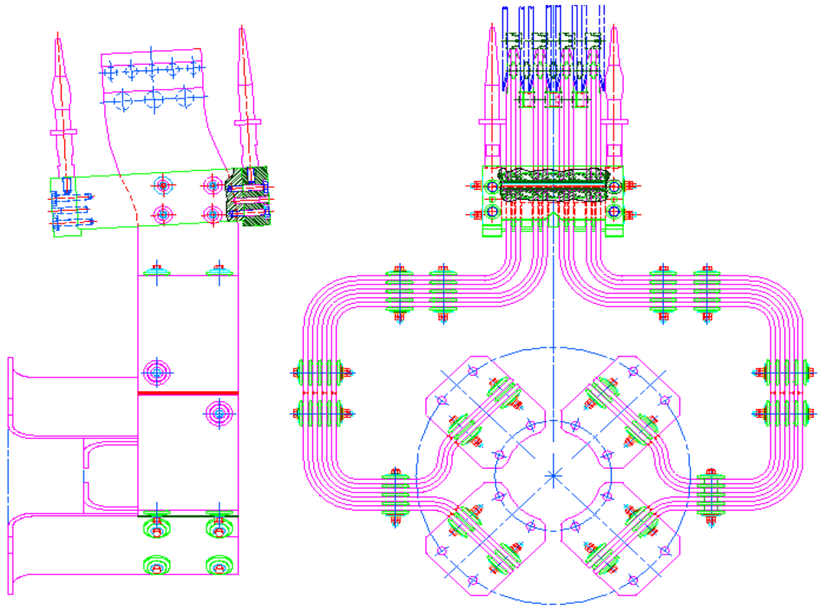


Figure 4.3-13**: Horn 1 Joint Cross Section and Elevation**

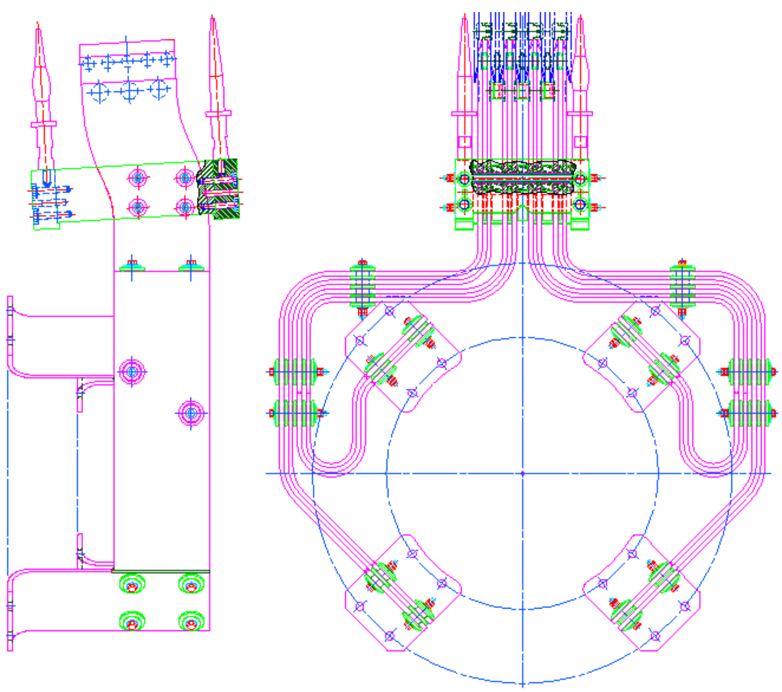


Figure 4.3-14: **Horn 2 Joint Cross Section**

4.3.5.3 Transmission Line Routing through the Shield Block and Beyond

The transmission line joint fingers connect with the transmission line section through the shield block at the remote clamp, as shown in **Figure 4.3-12**. The routing through the block is such to minimize weight and residual activation levels at the top of the block. Clamps and snubbers are used to minimize vibration. There are "quick" disconnecting joints at the remote clamp at the bottom of the module, at the top of the module, and beyond the edge of the T-blocks. In this manner, one can remove the section of stripline from top of module to beyond the module sides. Then one can remove the T-blocks, and the stripline-stuffing block. Next one removes the horn with transmission line joint and remaining stripline part in the module to work cell for replacement. At the work cell, one disconnects the section routed through the module from the joint and horn by disengaging the remote clamp.

The part of the stripline within stripline block (including the clamp) does not have to be replaced every time a horn is replaced. It is designed to last the lifetime of NuMI (10 years). The concern is that the fingers of the transmission line will "weld" together or somehow the remote clamp will not be able to disengage the transmission line and horn from the remainder of the assembly. Thus the stripline block is bolted together such that the transmission line internal to the transmission line block can be removed and replaced.

Airflow through stripline stuffing block from top of module to horn cannot be obstructed (this airflow cools stripline). However, an air dam is needed at the H-block cover between the module and the stripline along the target hall wall (this is a lower radiation area, so a wider choice of materials is available). The air dam is intended to contain air-borne radiation.

The transmission line along the target hall wall will be covered with a sloping "roof" to keep people from leaning on it or putting items on it. This will also help minimize the accumulation of dust and dirt on it.

4.3.5.4 Transmission Line Internal to the Horn Power Supply

The internal stripline of the capacitor bank is constructed of 1/4" x 12" copper extruded bus. Provision is also made to allow the output current direction to be reversed by the exchange of "jumper" placement. The output stripline is that section leading from the center bay of the capacitor bank to the outside of the enclosure. It is constructed of 3/8" x 12" 6101-T6 aluminum electrical bus conductor alloy.

The assembly of eight conductors, four conductor pairs, is held together by bar type compression clamps and utilizing G-10 insulating spacers between layers. The clamps are spaced at 12-inch intervals. The assembly is supported from an aluminum I-beam running the length of the enclosure. The I-beam serves two purposes. It serves as a spreader bar when the enclosure is being lifted by a crane for transport, but more importantly it facilitates the removal of the output stripline should it become necessary for repair or replacement. In the cavern installation, the output (stripline) end of the capacitor bank is closely positioned with respect to the cavern wall, preventing removal of the output stripline on that end of the enclosure. The stripline suspension incorporates a jacking mechanism and is equipped with rollers that trolley on the I-beam, allowing the suspension and stripline to pass through the enclosure and out the opposite end.

Pre-drilled holes in the I-beam flanges at each end allow extensions to be coupled and secured to the beam, as needed, to extend trolley travel.

4.3.5.5 Compression Clamps and Stripline Contacts

At locations where it is necessary to couple/decouple the eight-layer stripline, a special compression clamp is utilized. The clamp incorporates twelve spring-loaded pistons in each bar to establish equal pressure across the width of the stripline conductors. The spring on each piston is comprised of a series stack of 2,700 lb. rated conical (Belleville) compression washers. The clamp assembly is capable of 30,000 lbs. total clamping force.

4.3.6. Power Supply Cables

Table 4.3-2 through **Table 4.3-4** give the number, type, and approximate length of the cables needed for the power supplies, with the exception of the RG220 cable that is used for the kicker power supply. Klixon cables are not shown in this table, but are installed in the same manner as elsewhere at FNAL. All cables in new construction will be fire retardant.

4.3.7. Performance Monitoring Plan

For the kicker and horn power supplies, the predicted line locked ripple will not noticeably affect the beam dynamics, and Autotune will correct slow drifts. Other power supplies will have regulation as described in Section 0. All power supplies will also be continually monitored by the ACNET alarm system (with tolerances set appropriately). These alarms plus logged data will point out required power supply repairs. All supplies will have current error detectors, which will inhibit beam if the supply is not tracking the ramp.

4.3.8. References

The following references need to be made into NuMI notes.
Zhijing’s Notes
Horn PS Manual (too large?)
Safety Docs for MI8
T