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THE LEAD - LIQUID ARGON SAMPLING CALORIMETER OF THE SLD DETECTOR†

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ABSTRACT

The lead - liquid argon sampling calorimeter of the SLD detector is the largest detector employing cryogenic liquids now in operation. This paper details the design and performance considerations, the mechanical and cryogenic systems, the absorber design and tower segmentation, the data acquisition electronics, and the control systems of the detector. The initial operational performance of the device is discussed. Detailed resolution studies will be presented in a later paper.

I. INTRODUCTION

The SLAC Large Detector (SLD) was first proposed[1] in 1984 as a new detector to explore decays of the Z^0 at the Stanford Linear Collider. Detectors for physics at the Z^0 must be hermetic and must have excellent energy resolution and uniformity of response for both electromagnetic and hadronic energy depositions. Liquid argon sampling calorimeters satisfy these requirements. They offer good radiation resistance, allowing operation close to the beamline and inside magnetic fields. They may have arbitrarily fine longtitudinal and transverse segmentation and, being unity gain devices, they have inherently uniform and stable energy response. The absorber materials may be chosen to control the response to electromagnetic and hadronic showers.

In 1984, a simulation and test program was initiated by SLD to study the properties of liquid argon sampling calorimeters employing lead and uranium absorbers. The results of this program[2][3][4] provided a new understanding of the so-called compensation mechanism, first discussed in connection with uranium - scintillator calorimeters.[5] These tests demonstrated that for liquid argon sampling devices, equalization of calorimeter response to electrons and hadrons can be achieved by the use of common high Z absorbers such as lead and uranium. These materials are particularly efficient at absorbing electromagnetic shower energy, reducing the liquid argon sampling fraction below the level obtained for minimum ionizing particles and close to that obtained for hadronic showers. Amplification of the calorimeter response by the fission process in uranium is not observed, because of the saturation of the signal in the argon recoil. The equalization of calorimeter electromagnetic and hadronic response leads to improved hadronic energy resolution by minimizing the effects of fluctuations in the electromagnetic component of hadronic showers.

The calorimetry in SLD is implemented as a hybrid system. The first ~ 3 absorbtion lengths are composed of a finely sampled, conventional lead - liquid argon calorimeter (LAC), with electromagnetic and hadronic sections. The LAC is designed to contain $\sim 85\%$ of the energy of the jets in a hadronic Z^0 decay. The next ~ 4 absorption lengths are composed of a coarsly sampled, iron-gas calorimeter (WIC), operated in limited streamer mode.[6] The WIC contains the balance of the energy in a hadronic Z^0 decay, and also provides range information and tracking for muons. The region closest to the beamline is instrumented with two tungsten - silicon pad calorimeters, which provide electromagnetic coverage to within 28 mrad of the beam pipe and serve as luminosity monitors.[7]

The LAC is composed of a cylindrical barrel calorimeter and two endcap calorimeters, forming three distinct mechanical and cryogenic systems. The LAC is positioned within the SLD detector as indicated in figure 1. The barrel LAC inner wall, located at a radius of 1.77 meters, forms the outer wall of the Cerenkov Ring Imaging Detector (CRID). The barrel LAC extends to a radius of 2.91 meters, just inside the 0.29 meter thick, 0.65 Tesla solenoidal coil and the instrumented iron flux-return which forms the outer warm-iron calorimeter (WIC) and muon system. By positioning the LAC within the solenoidal magnet coil, 0.66 nuclear interaction lengths of uninstrumented absorber is avoided. The barrel LAC itself is supported off the arches of the detector, which also provide support for the coil and the WIC. The endcap LACs form two plugs, supported by the detector end doors. The plugs overlap the barrel sufficiently to close the solid angle, but leave a region around $33^0 \pm 2^0$ where dewar and support materials increase to a thickness of ~ 5 radiation lengths, degrading calorimeter performance . The barrel and endcap calorimeter system covers 98% of the full solid angle for both electromagnetic and hadronic showers.

II. CALORIMETER MODULES and TOWER SEGMENTATION

The barrel section of the LAC, covering the angular region $\theta \geq 33^0$, is composed of 288 modules mounted within a large cylindrical cryostat and sharing a common liquid argon volume (see figure 2). The full azimuth of the cylinder is spanned by 48 modules of width ~ 30 cm. The axial (z) direction is spanned by three modules (one "center" module and two "end" modules) of length ~ 2 m, attached to and separated by annular "washers" which are integral parts of the cryostat structure. Center and end barrel modules are very similar in construction, differing only in the sizes and layout of the towers. In the radial direction, two separate types of modules – electromagnetic (EM) and hadronic (HAD) – are mounted on top of each other.

The two endcap sections of the LAC, covering the angular range $8^0 < \theta < 35^0$, are each composed of 16 wedge shaped modules, again mounted within a common cryostat and sharing a common liquid argon volume (see figure 3). Endcap modules incorporate both EM and HAD sections in one mechanical unit. Endcap modules are functionally identical to barrel modules, with similar tower geometry, but there are basic differences in module design and construction.

LAC modules are constructed as parallel plate liquid argon ionization chambers. The absorber structure consists of alternate planes of large lead sheets and segmented lead tiles, with liquid argon filling gaps between the planes. The tiles in successive planes are arranged transversely and connected radially to form projective towers. The lead plates are grounded, while the tiles are held at negative high voltage and serve as the charge collecting electrodes. The use of lead as both the high Z absorber and the electrode structure makes a compact electromagnetic calorimeter possible.

The lead plates and tiles in EM calorimeter modules are 2 mm thick and are separated by 2.75 mm liquid argon gaps. This yields a longitudinal density of 0.79 X_0/cm and a dE/dX sampling fraction (energy deposited in liquid argon / total energy loss, for a minimum ionizing particle) of 18%. The EM calorimetry is divided radially into two separate readout sections to provide information on longitudinal shower development for electron/pion discrimination. The front section (EM1) contains the first 6 radiation lengths of material, while the back section (EM2) contains an additional 15 radiation lengths. The 21 radiation length thickness of the EM calorimetry is sufficient to contain 50 GeV electrons, with leakage (and leakage fluctuations) at the 1-2% level. The energy resolution for electromagnetic showers is expected to be 10-12%, including a 1-2% degradation due to material in front of the calorimeter.

The lead plates and tiles in HAD calorimeter modules are 6 mm thick and are separated by 2.75 mm liquid argon gaps. This yields a longitudinal density of 0.044λ/cm and a dE/dX sampling fraction of 7%. The HAD calorimetry is also divided radially into two separate readout sections (HAD1 and HAD2), each 1 absorption length in thickness. The total EM + HAD thickness of 2.8 absorption lengths is sufficient to contain 80-90% of the energy of a hadron shower. Energy leaking out of the LAC is measured in the WIC. The energy resolution for hadrons is expected to be approximately $60\%/\sqrt{E}$.

Table I summarizes the cell structure and the longitudinal segmentation of the EM and HAD sections of the LAC.

Table I. LAC Longitudinal Segmentation

LAC Section	Cell count	Cell X_0	Section X_0	Cell λ	Section λ
EM 1	8	0.75	6.0	0.030	0.24
EM 2	20	0.75	15.0	0.030	0.60
HAD 1	13			0.077	1.00
HAD 2	13			0.077	1.00

EM Cell: 2.0mm Pb, 2.75mm Ar, 2.0mm Pb, 2.75mm Ar
HAD Cell: 6.0mm Pb, 2.75mm Ar, 6.0mm Pb, 2.75mm Ar

Transverse segmentation of the LAC is provided by the segmented lead tiles. Tiles from successive layers are laid out in a projective pattern, and stacks of these tiles are ganged electrically into towers. The azimuth (ϕ) of the barrel is divided into 192 EM towers, each with an opening angle $\delta\phi = 33$mr. The polar angle (θ) of the barrel is divided into 34 EM towers on each side of the midpoint. The tile size increases with polar angle, so as to maintain a constant projective area for electromagnetic showers. The opening angle of an EM tower thus decreases from $\delta\theta = 36$ mr at the center of the barrel to $\delta\theta = 21$ mr at the end of the barrel. HAD towers are twice as large as EM towers in both transverse dimensions.

The endcap transverse segmentation continues the general tower arrangement of the barrel. In the EM sections, the azimuthal segmentation is also 192 at large radii, but falls to 96 and then to 48 at the smallest radii, to maintain an approximately constant projective area for electromagnetic showers. The polar angle segmentation follows the same philosophy, with the range $35^0 < \theta < 8^0$ divided into 17 segments. The transverse segmentation in the HAD sections is again twice as coarse as in the EM sections.

The segmentation of the LAC into modules and towers is summarized in Table II.

Table II. LAC Module and Tower Counts

Module type	Modules	Towers
Central Barrel EM	48	48(112+112)
Central Barrel HAD	48	48(24+24)
End Barrel EM	2(48)	96(84+80)
End Barrel HAD	2(48)	96(20+18)
Endcap (EM+HAD)	2(16)	32(117+105+27+21)
Total Barrel	288	32448
Total Endcaps	32	8640

III. MODULE ASSEMBLY

The design of the LAC attempts to maximize the active area of the calorimeter by placing internal support structures to the rear of the modules wherever possible, and by integrating the readout structure with the lead absorber itself. To achieve this, all modules are composed of a fully active lead absorber stack mounted on a thin aluminum support structure, stiffened primarily at the back. The modules are held together by stainless steel bands wrapped around the open sides. Figures 4 and 5 illustrate this module construction.

The lead used in the manufacture of both barrel and endcap modules is a "dispersion strengthened" lead alloy, containing $(1.50 \pm 0.25)\%$ tin and $(0.060 \pm 0.005)\%$ calcium, produced by Doe Run Corporation. This lead alloy achieves a minimum ultimate tensile strength of 8000 psi, and a minimum ultimate tensile yield strength of 7000 psi at 0.2% offset, when tested in the rolled direction. The creep under these conditions was found to be adequate for module construction and long term (one year) storage, providing the temperature was maintained under 85°F. Samples of lead from each melt were tested and certified by the manufacturer and a qualification test (stress to rupture) was performed upon receipt of materials.

In both endcap and barrel module construction, lead handling was an issue. The lead production, machining and handling process produces small slivers or chips of lead embedded in the lead surface. These chips come loose in later handling, or under application of high voltage. As part of our quality control procedures, all lead plates and tiles were examined and cleaned by hand, and all obvious lead chips were removed prior to module assembly.

(a) Barrel EM Module Construction

EM modules weighing 900 Kg are stacked on a flat 3/4" thick baseplate of 6061-T6 aluminum alloy. Bolted to the baseplate are two 1/4" thin trapezoidal aluminum endplates. The endplates are notched to accommodate radial aluminum rails (cross-section 5/8" by 3/4") on the cryostat washers, onto which the modules slide during detector assembly. Holes at the top of the the endplates match threaded keyinserts on the cryostat washer (see Section VI), to support the module radially from the ends.

Three long grooves (1/2" wide by 1/8" deep) are milled into the baseplates of the EM modules and fitted with long teflon and lead strips. These teflon and lead strips mechanically separate the lead plates and tiles in the module interior from the aluminum baseplate, allowing the lead to slide with respect to the aluminum in response to the differential shrinkage during cooldown to liquid argon temperature. Clearences of the endplates are chosen to allow a maximum lead – aluminum temperature difference of 50^0 C without danger of buckling the lead.

A vacuum lifting fixture was employed to lift and stack the lead plates, which span the full length and width of the module. The small lead tiles (typically 6 cm by 6 cm) were stacked in layers on top of the lead plates by hand. Every layer of the stack required a different set of lead tiles, sized and arranged to continue the projective tower pattern. In all, about 320 different tile sizes are used in the EM modules.

The loads within an EM stack are transmitted through the plates and past the tile planes by plastic spacers. These spacers also serve to maintain the 2.75 mm liquid argon gap to a tolerance of ± 0.08 mm. The spacers were injection molded of a glass fiber reinforced material, Celanese VECTRA A130. By controlling the flow direction of the fibers, spacers were produced with a bidirectional coefficient of expansion. The working direction was chosen to reduce the expansion coefficient along the length of the stack, while closely matching the shrinkage of the stainless steel tensioning bands. Additional spacers are used to separate the tiles from each other, with an intertile gap of 2 mm, and to hold the tiles in position and away from the open ends of the stack. A total of 16 different varieties of spacers are used in various locations in EM modules. The spacers fill roughly 1/4 of the intertile gaps and occlude approximately 5% of the lead area, in a generally non-projective pattern.

The lead tiles are ganged electrically into towers by wiring along the open sides of the module. Prior to stacking, all tiles have short pigtails of precut and prestripped 26 gauge copper wire soldered to them. The wire is silver plated and protected with an insulator combining kapton and teflon layers rated to 10 kV. The "buried" tiles in the center two rows of the module have their signals routed to the outside edges of the module, past the outer rows of tiles, by longer wire pigtails which run through precut grooves in the edges of the outer tiles. A 0.005" thin flexible strip of kapton circuit board is positioned diagonally along the exposed sides of the module to carry the tower wiring up to the top of the module on printed traces. The wire pigtails from individual tiles are soldered to the signal traces on this kapton circuit strip.

The lead plates are connected together electrically and grounded to the module baseplate (and eventually the argon dewar). Eight ground wires run up the sides of the module to connect the lead plates through a low inductance ground path.

Thin perforated lexan plastic sheets are placed over the exposed sides of the module to provide some protection for the delicate side wiring and to electrically insulate the tiles and wires from the stainless steel bands which will eventually hold the module together. At the top of the module, tower signals are connected from the traces on the kapton strips to pads on "signal highway" printed circuit boards by short wires soldered at both ends. The signal highway boards are described in detail later.

After stacking the layers of lead tiles and plates, and before wiring the tiles into towers as described above, four signal highway PC boards are placed on top of the module; each board covers half the module length and half the module width. A special aluminum top plate is then positioned on top of the boards. The boards are held loosely in position between the lead stack and the aluminum top plate by spacers captured in slotted oversized holes. This "floating" arrangement allows the signal highway boards to contract differentially with respect to the lead and aluminum to avoid buckling during cooldown. The top plate is a 1.1" thick ladder-like frame with two rows of 17 (center module) or 19 (end module) rectangular cutouts which provide space and access for the resistors, capacitors, and connectors on the signal highway boards, as illustrated in figure 4.

The stacked module is compressed by a series of pneumatic cylinders which apply uniform force on the top ladder plate. The electrical side wiring is completed at this point. Aluminum bars (1/4" thick by 1" wide by 12" long) are placed every 4 inches across the rungs of the top plate ladder between the cutouts. These bars are supported on the top plate rungs only at two points near their ends, so that they can flex under pressure, functioning as leaf springs. Stainless steel bands (1/2" wide by 0.015" thick) are then wrapped around the module, over each of the spring bars. The steel bands are tensioned over the base plate and spot welded permanently in place. When the external compression is removed, the bands hold the module together by compressing and deflecting the spring bars. The tension of the bands and the deflection of the springs are chosen to hold the module together under compression at both room temperature and during and after cooldown to liquid argon temperature. A compressive force of 2g, provided by tensioning the bands to 125 pounds, was chosen to provide a reasonable margin of safety in the event of an earthquake.

(b) Barrel HAD module construction

HAD modules weighing 2500 Kg are stacked on a 3/4" thick aluminum strongback support. The strongback is T-shaped, with an interior spine of width 1.125" extending 4 inches into the back of the lead stack to provide additional stiffness and support. Four fingers with slotted holes are machined on each end of the T-strongback; bolts through these fingers eventually mate with the washers and end-plates of the dewar to hold the module in place. Endplates bolted to the ends of the strongback are notched to slide onto mounting rails on the cryostat, as on the EM modules.

The strongback has 20 cutouts on each side, extending all the way to the edges of the module. These cutouts allow access to the signal highway boards from the back of the module, and also create 21 narrow fingers on which the steel tensioning bands rest. The strongback and banding arrangement is illustrated in figure 4.

The stacking order of a HAD module is reversed compared to an EM module, so the signal highway boards are loaded first, upside-down onto the strongback. In EM modules the tiles are mechanically floating, with the load transferred through the spacers and plates. HAD modules reverse this, transferring loads through the tiles and spacers, leaving the plates floating. To achieve this loading, HAD module lead plates have rows of 21 holes spaced every 4 inches along the edge, where interlocking spacers are captured. These rows of spacers correspond exactly to the positions of the steel bands, where the loads are maximal. Some 216 different tile sizes and 12 varieties of spacers are used to achieve the projective tower geometry in HAD modules. A typical tile and spacer layout is shown in figure 6.

HAD modules, with only two rows of tiles, have complete electrical accessibilty from the sides. The tiles are also thick enough to allow a simpler electrical ganging scheme. The pigtails and kapton signal strips of the EM modules are replaced with insulated wires for the entire tower wiring. The insulation is precut into short segments and positioned to expose the bare wire where it is stapled and soldered to the lead tiles. The lead plates are ganged together and grounded by similar side wiring at eight locations along the module, to provide a low inductance ground path.

As in the EM modules, springs maintain the tension of the bands which hold the stack together. HAD springs are formed of pairs of 2" wide aluminum base and spring bars, located at the front of the module, directly on top of the last lead plate. The stainless steel bands on HAD modules (3/4" wide by 0.030" thick) are considerably stronger than EM bands, to support the much greater module weight. The bands are tensioned to 400 pounds to provide a compressive force of 2g.

HAD calorimeter modules were stacked and assembled at a rate of three modules per week over a 13 month period, requiring roughly 20000 man-hours of labor.

(c) Endcap Module Construction

Endcap modules are functionally identical to barrel modules; there are, however, basic differences between the endcap and barrel module designs. Each endcap module incorporates both EM and HAD sections.

The endcap absorber structure is supported by an aluminum strongback known as the "shoe", which cantilevers the weight of the module from the back of the argon dewar. This is accomplished by sixteen or seventeen steel bands which exert force on the entire absorber stack to hold it in alignment by friction. Each steel band wraps over a 1/4" thick prestressed aluminum "top plate", along the sides of the stack, and under the aluminum shoe, where it compresses a copper-beryllium leaf spring (see figure 5).

The 5.5" high aluminum shoes were fabricated by sandcasting, followed by precision machining. Two types of shoes and modules were built, with staggered placements of the 17 or 16 springs and bands. This allowed modules to be installed alternately around the azimuth, with offset band positions, minimizing the gap between modules. The inner radius and outer radius ends of the shoe are bolted to straight aluminum support bars, known as "toe" and "heel" bars respectively, which run perpendicular to the shoe face up to the front of the absorber structure, so as to constrain the lead plates and hence the position of the entire stack. The toe and heel bars are eventually attached to each other at their front ends by radial straps during the final endcap assembly.

The endcap absorber structure again requires layers of different tile patterns to approximate projective geometry. The tiles are cut from lead plate using a numerically controlled punch, and the edges are chamfered on a brass wire wheel. The tiles are individually supported between the plates, with spacing (0.075 ± 0.015)", by 16 distinct shapes and sizes of spacers. The spacers are injection molded using the same plastic as in the barrel modules. The placement of the spacers is optimized to transmit the load from layer to layer in the stack and is generally non-projective. The spacers occlude up to 5% of the tile area in EM towers.

The longitudinal interconnection of tiles within a projective endcap tower is provided by a wire which runs perpendicular to the tiles and is soldered near the center of each successive tile. Since the tiles will be brought to high voltage, with the plates held at ground, each wire passes through lead ground planes through press-fit nylon insulators. The plates within a module are electrically connected by 8 grounding wires, which are soldered along the edge of the plates and attached to the support shoe. The wires corresponding to each tower within a longitudinal readout section (EM1, EM2, HAD1, or HAD2) originate at a printed circuit board which sits behind that section. These signal highway boards are fixed between each longitudinal section in the following way: behind EM1, the signal highway board is held between two 1/8" stainless steel plates, spaced 0.2 inches apart by steel spacers; behind EM2 the pattern is repeated; behind HAD1, 1/16" stainless steel plates and 0.1" steel spacers are used; behind HAD2 the signal highway board lies beneath a 1/16" aluminum plate supported by 0.1" aluminum spacers above the aluminum shoe. The steel and aluminum are chosen to minimize differential contraction during cooldown at each location, while the thicker plates used for the EM signal highway boards were chosen to approximately match the radiative thickness of a 2 mm lead plate. Due to the juxtaposition of aluminum, steel, lead, and plastic parts within the module, care was taken to provide for differential motion during cooldown to cryogenic temperatures. Where necessary, teflon tape was used to allow differential motion.

Additional space within the shoes behind the springs provides housing for circuit boards containing high voltage blocking capacitors. These capacitor boards are separate from the signal highway boards. (In the barrel, both functions are included in a single board.) The capacitor boards are connected to the signal highway boards by high voltage teflon + kapton ribbon cables which run outside the absorber stack along the outer radius edge. Three capacitor boards, servicing the EM1, EM2, and HAD sections of the module respectively, are packaged into a rigid stucture with nylon spacers and bolted as a unit into the inner shoe wall. This arrangement allows for access to the blocking capacitors during module contruction. The largest blocking capacitors, needed for the biggest hadronic towers, required up to 0.9" of space, necessitating close attention to clearances inside the module shoe.

The modules were assembled on a modified milling machine platform which provided a vertically movable table. The aluminum shoe was placed on the table, and the absorber structure was stacked onto the shoe from the bottom up. A movable swing arm was fitted to the assembly table to hold a prepared lead plate onto which the tile and spacer layout was performed. The completed plate + tile layer was then lowered onto the stack, where the wire-to-tile solder connections were made into precisely positioned holes in each tile ; in this way layout and soldering procedures were performed in parallel. The signal highway boards were added to the stack as appropriate layers were reached. While still on the assembly table, the completed absorber stack was banded and compressed to a precisely set tension. The modules were then moved to another working platform where highway board to capacitor board connections were made. The assembly labor for stacking and wiring all 32 endcap modules was 6 technicians working for 8 months.

IV. MODULE TESTING

Quality control testing was performed during all stages of module assembly, shipment, and installation on the detector. The most important electrical tests were high voltage performance tests and tower capacitance measurements. Mechanical tests, including a full liquid nitrogen cold test of every module, were also performed.

Module high voltage testing was performed by applying 3000-4000 Volts to all towers through the HV distribution system on the signal highway boards. In order to achieve low standing currents for a sensitive HV test, it was necessary to control the humidity in the assembly and testing areas. At later stages of module handling, the modules were wrapped in plastic and could be flushed with dry nitrogen gas to reduce the humidity. A standing current of no more than a few μA, spread uniformly over all towers, was required after an initial HV bake of 12-24 hours. Sparking was frequently observed during the initial application of high voltage, and could usually be traced to small chips of lead inside the stack, shorting a plate and a tile. A current draw of 10μA in a single tower (3000V through 300MΩ) indicated a permanent short, again usually caused by a sliver of lead. These offending lead chips were removed by hand.

High voltage testing was repeated many times for each module — after stacking, after shipment to SLAC, during and after cold testing, just before assembly on the detector, and in place on the detector. Although fewer problems were found at successive stages of testing, they never completely disappeared.

A capacitance test was performed on all modules, using a CAMAC-based measuring device connected to a personal computer. The capacitance tester read the capacitance of every tower through the normal readout cables connected to the signal highway boards. Tower capacitances could be measured to an accuracy of 1% and were identical for equivalent towers on different modules. The capacitance test easily uncovered shorted or disconnected towers or blocking capacitors and was precise enough to detect wiring problems as small as a single disconnected tile in a tower. Repeated capacitance testing was absolutely essential to the module checkout and repair efforts.

The normal capacitance test actually measured the series combination of the tower capacitance and the HV blocking capacitor, plus the extra capacitance of any cables, flanges and feedthroughs in the readout path. By deliberately shorting a tower, the capacitance of its blocking capacitor could be measured independently. The capacitances of towers and blocking capacitors of all types were measured in this way. Correction factors based on these measurements are used offline to compensate tower signals for the charge loss due to the blocking capacitors.

Capacitance tests were performed at all stages of module and detector assembly — on bare signal highway boards, directly on stacked modules before and after shipment to SLAC, during and after cold testing, through the signal cables and cold feedthroughs on the inner cryostat, and through the vacuum cables and warm feedthroughs on the outer cryostat. Capacitances were measured and recorded through the external warm feedthroughs with the modules warm, cold, and during and after filling with liquid argon.

At SLAC, all modules were put through a full cold test, to check both mechanical and electrical performance. Six modules at a time were loaded onto a frame, placed into a large test dewar, cooled to liquid nitrogen temperature over an 8 hour period, and then immersed in liquid nitrogen. The rapid cooldown cycle was achieved by a system which circulated cold gas within the dewar, through the modules, maintaining the differential temperature between lead and aluminum always less than 36°C. The modules were then brought up to 4 kV for 24 hours, while the HV power supply current was monitored by computer. During this test the modules were rotated within the dewar, while immersed in liquid nitrogen, to simulate all possible module orientations on the detector. Approximately 12 modules per week were cold tested in this fashion.

All 288 barrel and 32 endcap modules went through the cold test at least once. No mechanical problems were encountered, but there were a few electrical problems. While the full channel failure rate in the modules was very small, the cold testing pointed up many partial failures. In particular, weak solder joints in a section of the tower wiring were identified and subsequently redesigned. Modules requiring repairs (about 5%) were retested.

In the final capacitance tests before the initial cooldown of the LAC, there were only a handful of disconnected or shorted towers in the entire 40000 channel system. After the initial liquid argon fill of the barrel LAC, about 70 towers were shorted, when high voltage was applied. (HV shorts are counted by monitoring the current drawn by the HV supplies.) A later refill of the LAC resulted in 160 shorted towers in the barrel and 90 in the endcaps. In over one year of subsequent operation, the number of shorts has increased slowly, remaining less than 1% overall.

V. TOWER SIGNALS, CABLING, FLANGES and FEEDTHROUGHS

(a) Signal Highway Board

The ionization charge collected on calorimeter towers is routed through special "signal highway" PC boards (SHB). These boards are integrated into the module structure, immersed in liquid argon. The barrel module SHB design is described in the following discussion. The endcap design is similar, although the board layout and placement within the module is different. (In particular, the functionality of a barrel SHB is implemented on two separate boards in the endcaps.)

The barrel module SHB are large (36" long by 5" wide by .064" thick) G-10 boards, copper-clad on both sides. Four such boards occupy the outermost layer of each barrel module. Tower signals reach the SHB on pads along the edges of the board, to which the tower wiring is soldered. Since the calorimeter towers are operated at high voltage, blocking capacitors are needed to couple the signals to the external electronics. Most of the space on the SHB is used to house these large capacitors. The SHB also distribute high voltage to the towers, through individual resistors connected to a common HV bus. Tower signals leave the SHB on ribbon cables which plug into connectors on the board.

The SHB circuit for each tower contains two or four 6kV blocking capacitors, a high voltage supply resistor, and a protection resistor, as shown in figure 7. All traces are pre-tinned, and areas of the boards which bus high voltage in proximity to grounded structures in the module are covered with a thin conformal-coating epoxy (HYSOL-PC12-007). Materials with flame retardants (solder mask and FR-4 epoxies), which can contaminate liquid argon, were avoided. Once loaded with components, all 1200 signal highway boards were thoroughly tested by HV cycling both in air and in liquid nitrogen for four days.

The HV blocking capacitor for each tower is actually implemented as two capacitors in series (EM towers) or four capacitors in series and parallel (HAD towers). Pairs of capacitors are connected in series so that a single failure (short) will not disable the tower. The capacitors are cylindrical Mylar foil, epoxy sealed capacitors (American-Suzuki-X675), with low inductance internal contacts. These capacitors were selected after an extensive program of thermal and high voltage testing. Many capacitors which perform well when warm are unsuitable for use in liquid argon, due to large capacitance changes, leakage, or high voltage breakdown. The chosen capacitors exhibit a $12 - 13$ % decrease in capacitance when cooled from 300^0K to 86^0K. Capacitors ranging in value from 1.5 nF to 28 nF were used as needed to obtain at least 4 times the tower capacitance, providing a charge transfer efficiency of at least 80%.

The high voltage supply resistors are 10 kV, 300 $M\Omega$, 1 W custom thick-film ceramics (TRW-TFRB-1). The large resistance limits the current drawn by a shorted tower, and also provides RC filtering of the supply voltage. An additional 2.5 kV, 3 $M\Omega$, $\frac{1}{2}$W resistor (TRW-TFRG-1) is provided to complete the ground path (when the preamp is disconnected) and to protect the signal readout cabling and feedthroughs from a doubly shorted blocking capacitor. The ceramic resistors are thinly glazed to eliminate leakage, while still able to survive differential contraction during cooldown.

(b) Cabling

Signals are taken off the SHB on 26 and 34 conductor PTFE teflon ribbon cables, with alternating signal and ground wires. Teflon was used to avoid problems of brittleness which occur in other insulators, as the cables must be able to flex during cooldown, warmup, and in modest earthquakes. Cables run along the top of the barrel modules and through the interior of the endcap modules. The maximum cable length is 3 meters from the SHB to the inner wall of the dewar. The cabling scheme, from module to external electronics, is illustrated schematically in figure 8.

At flanges on the inner dewar, the cables plug into special transition circuit boards (see figure 8). The transition boards lie on top of the flange and typically group 3 cables into a single 55-pin connector, which in turn plugs into a hermetic feedthrough in the flange. Grounds are collected onto 6 of the 55 feedthrough pins.

Signals are carried through the vacuum space to connectors on the outer dewar wall on bundles of 1 meter long, 0.0126" diameter nickel alloy wire with a double polyurethane coating (Carpenter Technology Corporation alloy 180). This wire has a low thermal conductivity of 0.4 watts/cm-^{0}K and a resistence of 3.68Ω/m. It also has the advantage of being heat strippable and solderable with Pb-Sn solder and organic fluxes. The heat load in the barrel from all signal wires is approximately 85 Watts.

Wire used to carry high voltage both in the argon and in the vacuum space is a multiconductor strand with two layers of teflon insulation (Gore PN F018090), rated at 18 kV. The wire contains no ground shield, but was additionally protected with teflon spiral wrap in critical areas near grounded surfaces.

(c) Signal Flanges and Feedthroughs

In the barrel, all electrical signals from the modules penetrate both the argon and vacuum vessels through feedthroughs on 24 main flanges on each of the annular endplates. As central barrel modules are divided in half electrically, with signals routed to both ends of the detector, each flange effectively serves 6 modules (2 end EM + 2 end HAD + 2(1/2) central EM + 2(1/2) central HAD). In each endcap, 32 similar but smaller flanges hold the feedthroughs which penetrate the argon vessel. As design and construction details are similar, only barrel flanges and feedthroughs are described here.

The flanges in the cold argon dewar wall are 12" in diameter and are fabricated from 5083 aluminum alloy, the same material used for the dewar. Each flange has 19 feedthrough holes, as shown in figure 8. LAC tower signals occupy 15 feedthroughs, 1 feedthrough is reserved for cryogenic instrumentation (thermocouples and resistors), and 2 feedthroughs are used to supply high voltage to the modules (one for EM modules and one for HAD modules). The remaining feedthrough hole structurally symmetrizes the mechanical forces within the flange, but is capped.

Signal and instrumentation feedthroughs (based on Hermetic Seal Corporation part number HSC-X960504-22-55P-2) are 1.625" in diameter and contain 55 gold-plated pins, giving a flange signal density of 8.8 pins per square inch. The feedthroughs and pins are made of Inconel X-750 alloy and have thermally matched, fused glass to metal seals.

As the leak-tight integrity of the feedthroughs and flanges is critical to the maintenence of the insulating vacuum, a 100% testing program was carried out for all elements of the design. The 55-pin feedthrough parts were individually certified at 1×10^{-10} cc He/min, and then electron beam welded into individual 2" diameter rings of aluminum-stainless steel roll-bonded transition material (manufactured by Spur Industries), with a final bond-line thickness of 0.265". The combined pieces were then recertified after thermal cycling five times from 320°K to 82°K. Next, the feedthrough plus transition ring was electron beam welded into the main aluminum flange. Electron beam welding on a numerically controlled table produced welds of 0.050" penetration uniformly, with consistent and low heating of the critical transition joint. In total, the cold flange system contains approximately 2400 welds.

O-ring grooves were machined into the flanges, to accept Indium O-ring seals for leak checking at 50 psi. The assembled flange underwent five thermal and pressure cycles, with Helium leak checking at liquid nitrogen temperature, and was then recertified. The 48 barrel flanges were finally TIG welded into the argon dewar endwall and pressure and leak checked *in situ*. There were no flange failures.

Each vacuum endplate of the barrel contains 24 flanges of 16" diameter. These flanges are fabricated from 3033 stainless steel and have double Viton O-rings, with individual pumpouts. The use of stainless steel for the warm flanges avoided the need for transition pieces or individual O-rings on each of the approximately 1200 feedthroughs. The flanges are machined with 16 deep slots which match (and align) the external preamplifier board connectors (see figure 8). Each of the 16 slots has an EDM processed weld preparation, allowing D-style feedthroughs to be directly electron beam welded into the flange.

The D-style feedthroughs (custom made by Hermetic Seal Corporation) contain 50 glass-sealed Inconel pins in an Inconel X-750 body. The thickness of the flange (3cm) and the orientation of the D-shaped slots was governed by the feedthrough design, which precluded sagittal deflections greater than 0.0001" under (test) vacuum loading. The inside pins of the feedthrough are pierced, flattened, and pretinned for soldering. The outside pins are round and mate directly into the D-style preamplifier board connectors, avoiding the need for additional cabling.

After welding, pressure tests, and leak check certification, the warm flanges were fitted with vacuum signal cable assemblies, in preparation for installation on the detector. The vacuum flange signal cabling consists of 1 meter long wire bundles, with wires soldered and stress relieved to the pierced pins on the inside of the flange, and connected to a plastic 55-pin connector at the other end. The cable connectors plug into the mating feedthroughs on the cold flange as part of the final flange installation procedure, just before the warm flanges are bolted up to seal the vacuum vessel.

(d) HV Feedthroughs

Each argon and vacuum flange in the barrel contains two HV feedthroughs, one servicing EM modules and one servicing HAD modules. The endcap arrangement is similar. The argon HV feedthroughs (custom made by Insulator Seal Corporation) are rated at 10kV. A cross-section is shown in figure 9. The double-walled feedthroughs are made of a ceramic and nickel alloy, brazed to a stainless steel base. The region between ceramics is pressurized with nitrogen gas at 8 psi. The double-wall construction prevents a single ceramic seal failure from creating a leak into the vacuum space.

The vacuum flanges have two 5kV BNC-style ceramic feethroughs (Insulator Seal Corporation PN9231001) welded into them. As these flanges are accessible from the outside, only a single-walled ceramic was used. The same teflon HV wire employed in the argon space is used to connect the cold and warm flange feedthroughs through the vacuum space.

VI. MECHANICAL SYSTEM and ASSEMBLY

(a) LAC Mechanical System

The LAC vessels consist of a set of four concentric, ~6 meter long aluminum cylinders, with annular endplates of ~2 meter inside radius and ~3 meter outside radius. The inner vacuum and argon cylinders, the outer argon and vacuum cylinders, and the endplates create a dewar enclosing the calorimeter modules and liquid argon, as illustrated in figures 2 and 3.

Aluminum alloy 5083 was used for all cylinders, to provide maximum strength with minimum wall thickness. Aluminum is superior to stainless steel for this application, but does introduce some unique problems. As we discovered through painful experience, aluminum welding is an expert craft, requiring carefully trained and certified personnel, working with techniques and equipment specifically matched to the welding task at hand.

The dewars do not rely of the subsequent presence of the modules to achieve mechanical strength, but are designed and tested as independent pressure vessels. Table III summarizes the dewar dimensions, wall thicknesses, and pressure ratings. The barrel argon vessel is rated at 49 psi to accommodate the the static liquid argon head (13 psi), the vacuum load (15 psi) and filling (15 psi), plus an operating range overpressure (6 psi). The vacuum vessel must be able to handle both the normal vacuum load and the additional liquid weight in the event of an argon spill into the vacuum space between the vessels.

Table III. LAC Dewar Dimensions

Vessel or Feature	Inside Radius (in)	Z Position (inner) (in)	Wall Thickness (in)	Over Pressure Rating (design/test) (psi)	Under Pressure Rating (design/test) (psi)
Barrel					
Inner Vacuum Cyl.	69.875	-	1.125	15/22.6	15/vacuum
Inner Argon Cyl.	73.388	-	1.250	49/74	15/vacuum
Outer Argon Cyl.	109.813	-	1.375	-	-
Outer Vacuum Cyl.	113.187	-	1.375	-	-
Argon Washers	-	± 40.722	0.780	-	-
Argon Endplates	-	±123.937	3.848	-	-
Vacuum Endplates	-	±134.167	2.250	-	-
Endcap					
Inner Vacuum Cyl.	7.875	-	1.500	15/22.5	15/vacuum
Inner Argon Cyl.	10.500	-	1.250	47/71	15/vacuum
Outer Argon Cyl.	63.808	-	1.062	-	-
Outer Vacuum Cyl.	66.062	-	1.250	-	-
Vacuum Faceplate	-	±87.086	1.500	-	-
Argon Faceplate	-	±89.836	1.500	-	-
Argon Backplate	-	±125.961	1.500	-	-
Vacuum Backplate	-	±139.179	2.750	-	-

The inner argon vessel provides all the mechanical support for the modules. In the barrel, it is a cylinder stiffened by annular endplates and two additional annular rings (washers) welded in place at the one-third points along its axis. In this manner, three 2 meter long compartments are formed for the modules. The washers each contain 48 penetrations of 2" diameter to allow cables from the center modules to pass through to the ends. The endcap vessels have no intermediate washers, but the front and rear endplates are tied together by 16 aluminum rods of diameter 2cm, spaced azimuthally around the cylinder. These "tie rods" transfer most of the load to the argon backplate and hence allow the use of thinner front walls.

(b) LAC Assembly Sequence

Loading of modules onto the cryostat took place in a large clean room area (40x30x20 m^3) in the experimental collider hall. The electromagnetic modules require support at the two ends and center, while the hadronic modules have an embedded T-beam strongback, and require only end support. Endcap modules require support from the shoe only. Given the proper external support, the modules may be rotated at any angle around their longitudinal axes, facilitating installation.

The inner argon dewar endplates and washers contain radially oriented guide rails which act both to align the modules during insertion and to support the modules in place. The rails were baked with a hard teflon finish to reduce friction and the resulting production of aluminum slivers when module endplates slid against them during insertion. A teflon lubricant was also sprayed on the module endplates before insertion. Once inserted into position, the endplates of the EM modules are bolted to the dewar washers and endplates. Each electromagnetic module requires one additional support at the center of its baseplate, provided by a radial bolt penetrating the inner argon cylinder. Hadron modules are supported soley by the fingers on their T-shaped strongbacks, which extend over and are bolted to the lips of the dewar washers and endwalls.

The barrel modules were loaded radially onto the inner spool piece (see figure 2) by a device that picked them up, rotated them, and then attached to the spool itself at the proper compartment. The installation tooling allowed a fine adjustment to accurately guide the modules onto the alignment and support rails, while providing support during insertion. EM and HAD module loading started from the top of the spool and proceeded down both sides in parallel, finishing at the bottom. Module loading onto the spool was performed by crews of 3-4 technicians (installation) and 3-4 physicists (cabling and testing) over a 3 month period, requiring 13000 man-hours of labor.

The modules in the barrel are positioned by the radial rail and endplate system with azimuthal gaps of 0.48 inches between modules. About half of this separation represents the mechanical tolerence in module construction, and about half is required clearance for motion in an earthquake. A 1.75" gap between the top of an EM module and the bottom of the corresponding HAD module was required for signal cabling and also as clearance for HAD module flexing in an earthquake.

During loading, the barrel argon vessel and modules were supported along the longtudinal axis on a large extendable box beam. Once module loading and testing was complete, the outer argon shell was slipped over the spool and bolted on. A narrow aluminum seal was welded over the joint. By placing O-rings in the initial bolt-up configuration to isolate the joint from the cryostat and module volume, leak checking of the seal welds and other penetrations was expedited. The outer vessel also had 60 kW of heaters and 11 liquid nitrogen cooling loop circuits and manifolds pre-welded to it (see next section).

Once the argon vessel was seal-welded and wrapped in 12 layers of superinsulation, it was moved into the vacuum vessel, which had been pre-mounted inside the detector magnet. The move was accomplished by rolling the argon cylinder on the box-beam, which had been extended through the detector. Once the argon vessel was rolled inside the vacuum vessel, the internal cryogenic plumbing was completed and tested. Cryogenic penetrations into the barrel vacuum vessel are placed radially on the ends of the vacuum cylinder, while penetrations of the argon vessel are made through the endplates. In the endcaps, penetrations are made through the backplates.

The barrel argon vessel load was transferred from the temporary assembly beam to two vacuum jacketed, crossed stainless steel slings at each end of the cylinder (see figure 2), which capture the extended lip of the inner argon cylinder and hang off eccentric pins on the detector arches. The vacuum housings of the slings penetrate the dewar vacuum wall, forming a common jacket. At the eight points of penetration, vacuum welds and structural welds support the 20 ton vacuum vessel and calorimeters.

The vacuum inner cylinder was installed on a smaller beam, and the two vacuum endflanges bolted on. The vacuum seal is made with double Viton O-rings, with pumpouts.

The endcap was assembled as shown in figure 3, with the argon dewar backplate in the horizontal plane. The modules were lowered vertically onto the backplate and held in place with dowels. The azimuthal gap between adjacent modules was 5/16". When all modules were loaded into place, the 16 tie rods connecting the front and back endplates were inserted. The argon cylinder and front plate were lowered down over the modules and bolted to the tie rods. After completing and testing internal cryogenic connections, the argon vessel was wrapped in superinsulation and the vacuum vessel was lowered over the argon vessel. The entire unit was then tipped into the vertical orientation and bolted to the detector door.

(c) Earthquake Protection

The LAC is designed to survive an added 0.7 G acceleration in any direction. The support slings of the barrel provide protection against earthquakes that drive the hanging system orthogonal to the detector axis. The slings dynamically decouple the LAC vessel from the detector body by lifting alternately off the support pins. This results in a shifting of the resonant frequency of the structure from 6 Hz to 21 Hz, damping the oscillations. The modules and internal spacings have been designed to survive the 3.5 G acceleration associated with this motion. Protection against a maximum longitudinal deceleration of 0.7 g is provided by a system of 16 hydraulic shock absorbers which penetrate the vacuum wall and transfer the load from the cold wall of the LAC to the steel doors of the detector, and from struts on the doors to the walls of the experimental hall.

The protection system was first exercised, while only partially installed, on Oct. 17, 1989, during the Loma Prieta earthquake. At the time of this quake, the system was under insulating vacuum, but was not filled with liquid argon. Only one half of the hydraulic shock absorbers were in place. The 750 ton vessel was subjected to a vertical loading of 0.25 g and a nearly axial horizontal loading of 0.30 g, and sustained no detectable damage.

VII. CRYOGENIC SYSTEM and CONTROLS

(a) System Organization and Control

The cryogenic system for the LAC is shown schematically in figure 10. The barrel and two endcaps form three distinct cells for control purposes. Each cell is serviced by three subsystems: vacuum, nitrogen and argon. Liquid nitrogen is used to cool the liquid argon, through a liquid nitrogen supply system and a gaseous nitrogen vent system.

The vacuum, nitrogen, and argon subsystems are controlled by eighteen independent microprocessor based process controllers (Taylor Micro Scan 500RA), which monitor temperatures and pressures in the cryogenic systems, and open and close proportional control valves in programmable feedback loops. The activities of the controllers, readings of transducers (thermocouples, RTDs, vapor pressure thermometers, and cold cathode vacuum gauges), and states of valves are monitored continuously by a microVax computer. State control decisions for binary valves which maintain the integrity of the system are made by a set of “cryogenic interface modules” (CIMs). These CAMAC modules read back the state of critical valves and selected transducers to perform programmed logic decisions, overriding or altering the state of the system, dependent soley on their input.

(b) Vacuum System

The barrel (endcaps) vacuum system employs two (two) Leybold 150 liter/sec turbomolecular pumps to maintain an insulating vacuum of about 10^{-5} Torr in each cell. These pumps are supported by three mechanical roughing pumps (each 75 cfm), for initial purging and pumpdown. All pump controls and gate valves are interlocked to avoid oil contamination. Cold cathode ionization gauges (Varian) monitor the main vacuum and interlock the turbomolecular pumps and the warm-up heater power. One of the three roughing pumps remains on emergency (diesel) power, to accommodate power outages. The vacuum system of each cell is connected by a large diameter ball valve (see section (e) on safety), with Teflon seats suitable for cryogenic operation, to an 8” vacuum vent line that exits the building.

(c) Nitrogen System

The liquid argon cryostats of each cell are insulated by vacuum and superinsulation between cylindrical vessels. They are cooled by liquid nitrogen circuits formed of aluminum extrusions of rectangular outer cross section and 1/2" diameter bore, welded to their exterior and pressurized to about 20 psi. The total conductive, convective and radiative heat loss of the system is estimated to be less than 1000 Watts, including the 40000 electronics wires passing between the inner and outer dewar walls.

The nitrogen system has a single vacuum insulated liquid supply line (1" diameter) and a gas phase return line (2" diameter). Nitrogen coolant is stored in a 100000 liter tank outside the experimental hall, and transferred to a smaller 570 liter conditioning and holding tank on the detector . The external storage vessel is at the surface level and requires 150 feet of vacuum insulated transfer lines to carry the cryogens to the detector. A drop of 50 feet in elevation to the holding tank produces a pressure head of about 50 psi. Once on the detector, cryogens are distributed to the three cells through main manifolds. The manifolds connect to the two endcaps by flexible transfer lines which ride on Gleason carriages. This arrangement allows the end doors of the detector to open, without disconnecting transfer lines, pausing the liquid nitrogen cooling, or emptying the liquid argon itself.

Barrel and endcap temperatures are controlled by the liquid nitrogen cooling loop circuits. The barrel loops have two inlets at the bottom of the vessel and four outlets at the top, while the endcaps each have one inlet and two outlets. In the barrel, the loops cool the two annular surfaces, while in the endcaps, the larger area of the faces is also cooled. Nitrogen gas exiting the loops is vented outside the building, while excess liquid nitrogen exiting the loops is first vaporized in a heated dump sump, then vented outside the building.

Temperature feedback is provided by sets of vapor pressure thermometers and pressure transducers welded to the argon vessel near the inlet and outlet of each cooling loop. These transducers are connected to the process controllers which modulate the inlet and outlet proportional valve positions.

In normal operation, valves at the loop inputs and outputs are cycled open to fill the loops with liquid at about 20 psi. The outlets are then closed, and the vessel is cooled by the expanding liquid. The outlet valve is cycled open to refill the loop.

During cooldown, the valves are cycled more frequently, under computer control. The typical cycle time is about 20 minutes, with liquid flowing for about 3 minutes in the loops. This cycle is adjusted manually, to cool the vessel uniformly, without inducing large temperature differences (over 50^0C) between aluminum vessels and module lead.

Operationally, the impedance of the very long 1" supply lines created initial difficulties, requiring us to carefully rotate through the liquid nitrogen loop valve cyclings during cooldown and operation, to avoid pressure drops in the cooling system. An additional pressure building circuit in the storage tank was subsequently added, to improve the system performance.

(d) Argon System

The argon system is operated as a closed cryogenic system, to avoid contamination with air. Argon is supplied from a 50000 liter storage tank at surface level, through a single 2" vacuum-insulated transfer line. This transfer line also acts as the gas phase return line. The storage tank is equipped with a pressure-building external heat exchanger, which allows the pressure over the argon to be raised rapidly to 20-30 psi, to expedite detector filling. The liquid phase supply line enters at the top of the vacuum space and connects to the bottom of the argon vessel of each cell. A 2" gas phase line is connected to the top of each cell, and to the gas phase return of the Argon conditioning tank. The conditioning tank has cooling capability and provides argon pressure regulation in each cell over the liquid. In addition, an emergency vent line is attached to the gas phase, allowing the venting of argon through a dump sump and out of the building if over-pressures occur. This vent system is terminated in a flapper valve, and backfilled with argon gas, to avoid contamination.

The argon system was originally designed to fill the cryostat from the bottom with liquid, while providing a 2" gas phase return line at the top into the conditioning tank. This system was used once, with unfortunate results. Liquid entering at the bottom of the cryostat agitated and floated up lead slivers, creating shorts within the modules. The filling procedure was modified to bring liquid into the cryostat through the gas phase lines at the top of each cell.

To reduce boiling of the argon, the lead modules and cryostat are super cooled to 80^0K with helium transfer gas, before starting the filling. Before introducing liquid argon, the helium is removed and argon gas is allowed to condense and rain within the cryostat. Cooldown for filling takes about 10 days, while the liquid fill takes about 12 hours. Topoff is done with gas from the conditioning tank.

In operation, the cells are operated with the gas phase and vent valves closed, substantially isolating them from the long transfer lines and manifolds to reduce the chance of contamination. Pressure regulation is then done solely by the liquid nitrogen cooling loops, rather than the argon conditioning tank. Pressure is maintained over the liquid at about 6-8 psi. The liquid phase valves at the cryostat are disabled.

(e) Safety System

Asphyxiation associated with a significant liquid spill was deemed the primary hazard associated with the use of liquid argon and nitrogen in the LAC. The LAC safety system is designed with the philosophy of reducing the amount of liquid capable of spilling in a confined area in any conceivable sequence of accidents. A complete analysis of all credible accidents leading to significant spills was performed,[8] and the detector detector safety systems designed accordingly.

In general, all critical control, valve state readback and monitoring circuits are supplied with uninterruptable (battery) backup power, all critical valves are air operated, and the loss of control power or air pressure always results in the return of these valves to a safe state for the system.

All liquid supply and return transfer lines are segmented into small sections, each protected by Barksdale pressure switches interlocked to the supply. In the event of a loss of insulating vacuum through external or internal transfer line rupture, the main liquid supply valves at the storage tanks, and at the entrance to the experimental hall, are automatically shut, thereby isolating the large reservoirs of liquid. The liquid volume spill potential is reduced to that in the transfer line (about 100 liters) at the time of rupture. The strorage tanks themselves are surrounded by a retaining wall dam, capable of holding their content and allowing a slow boiloff.

The only other significant source of liquid cryogen is the 35000 liters of argon in the detector itself. The rupture of any of the three argon vessels would result in the spill of liquid into the vacuum space, filling it to about its midpoint in elevation. The vacuum vessel is designed to contain the resulting hydrostatic and pressure load, and little liquid would exit the vacuum vessel end flanges because all the major seals are welded or are glass to metal. The liquid phase supply line of the argon system enters at the top of the vacuum vessel, and threads its way down in the vacuum space to the bottom of the argon vessel. In this way, in a cryostat rupture, liquid rises in this pipe within the vacuum vessel itself, and does not exit through the top. If the pressure increases over the boiling liquid in the vacuum space, liquid may be driven out of the fill lines and into the manifolds and transfer lines, conceivably creating a spill if these external lines are ruptured. To prevent this, the large cryogenic ball valves automatically open to the vacuum vent, whenever a loss of the main insulating vacuum is detected. This reduces the pressure on the liquid, preventing any from being driven out the fill lines. Any residual liquid driven into the argon gas phase or vent lines is boiled off and vented outside, after passing through the heated emergency dump sump. The emergency vacuum vent valves are operated off an independent air ballast reservoir and the system is also backed by a large passive relief valve. Through these largely passive techniques, a significant liquid spill is rendered impossible.

VIII. LAC ELECTRONICS and CONTROL SYSTEM

The overall architecture of the LAC control system is divided into three major branches, one for event readout and two for monitoring and control.

The LAC readout chain consists of a FASTBUS timing module, detector mounted electronics (providing amplification, serialization and digitization), 32 FASTBUS slave modules (providing calibration and data reduction), a FASTBUS master module (which assembles complete events from the slaves), a process on the data acquisition VAX computer to pull events out of FASTBUS and put them in a shared event pool, and another process on the data acquisition VAX to read events from the event pool and write them to tape.

The first branch of the monitoring system provides computer monitoring of low voltage power supplies and computer moniroring and control of high voltage power supplies, through a CAMAC system connected to the data acquisition VAX computer. Power supply voltages and currents are monitored continuously and written frequently into a large database, where they are checked against preset tolerances. Selected information is transferred to a time-history facility for longer term monitoring.

The second branch of the monitor system provides computer monitoring and control of the LAC cryogenics, through a CAMAC system connected to an independent microVAX computer. This microVAX is attached to an uninterruptable power supply and is responsible for maintaining the cryogenic integrity of the LAC. The microVAX monitors and controls a large number of cryogenic parameters, including temperatures, pressures and valve statuses, as discussed in a previous section. As a secondary function, it also monitors temperatures and voltages read from special boards embedded in the front-end electronics.

(a) LAC Front-end Electronics

The front-end electronics system for the LAC consists of charge sensitive preamplifiers, analog storage and multiplexing circuits, analog-to-digital converters, and associated power, control, calibration, readout, and monitoring devices. Performance requirements, as well as space and budget constraints, led to a design containing several novel features. These include the installation of the front-end electronics directly on detector, eliminating completely the need for low level signal cables external to the cryostat, the acheivement of low noise levels without the use of transformers, allowing the electronics to operate inside the detector magnetic field, the extensive use of channel multiplexing to minimize cable plant volume, and the removal of power from the preamplifiers between beam crossings to minimize power dissipation. Extensive use of custom integrated circuits, dense hybrids, and unique packaging makes these solutions practical. The 120 Hz frequency of the SLC beam crossings, allowing over 8 ms between events for online data processing, was exploited throughout the entire electronics chain.

The LAC front-end electronics has been described in part elsewhere[9] but will be discussed in more detail here. The front-end electronics is packaged in sub-assemblies which, due to their shape, are called "tophats". Tophats are mounted directly on the signal feedthrough flanges on the outside of the liquid argon cryostat. The logical layout of the electronics within a LAC barrel tophat is shown in figure 11, along with the connections from the detector to the tophat and from the tophat to the external control and data acquisition systems. The organization of the signal processing boards within a tophat is charted in figure 12. A more detailed diagram of the tophat signal processing electronics is shown in figure 13.

The tophat enclosure provides a suitable mechanical, electrical, and thermal environment for the front-end electronics. Due to differing flange arrangements and space limitations, the packaging for the endcap LAC is somewhat different than for the barrel LAC, but they are functionally identical and the same signal processing boards are used. The mechanical configuration described here is that of the barrel LAC system.

Tophats are cylindrical aluminum enclosures, 16" in diameter and 5" in height, mounted on top of the vacuum flanges which carry calorimeter signals out of the detector. The mechanical tophat encloses a printed circuit motherboard, mounted and grounded directly to the flange, which in turn supports a collection of signal processing daughterboards. The tophat enclosure provides mechanical protection and electrical shielding for the front-end electronics. It also serves as a heat sink, with chilled water circulating through a tube welded around its base. Aluminum fins, welded to the inside of the tophat body, extend between the daughterboards to help to conduct heat away from the preamplifiers and to act as shields against crosstalk between daughterboards.

We have taken advantage of the low SLC repetition rate (120 Hz) to reduce the front-end power consumption by turning off the preamplifiers between beam crossings. Each tophat contains a power supply board which provides local energy storage capacitors and voltage regulation. The preamplifiers are turned on 1 ms before each beam crossing, providing a warmup time sufficient to stabilize the outputs before the arrival of a real signal. This power pulsing scheme reduces the power consumption and resulting heat generation of a tophat from nearly 500 W to approximately 60 W. Additionally, the power supplies, in racks on the top deck of the detector, only need to supply the average current, reducing supply and cable costs.

Tophat operations are directed locally by a controller board, which receives commands and timing signals from an external FASTBUS Timing and Control Module (TCM). Control signals are sent from the TCM on a set of three optical fibers – clock, command, data – using a standard SLD protocol. The signals are converted from optical to electrical form before arriving at the tophat. The tophat controller synchronizes all tophat operations — power pulsing, signal sampling, digitization and readout — to the TCM timing signals, and also controls various tophat operations, such as setting calibration voltages and channel calibration patterns. To protect against failures which would cripple the operations of an entire tophat, the controllers have built-in redundancy. Control signals can be sent from the TCM to the tophat on either of two identical sets of fibers and cables, and within the controller most functions are implemented independently for both control paths.

The analog signal processing of the ionization charge collected on a calorimeter tower consists of amplification, shaping, sampling, analog storage, and digitization on a multiplexed ADC. Sensitive amplifier inputs are protected from high voltage discharges. A high precision internal calibration system is provided. The digitized signals are transmitted from the tophat to the FASTBUS system on top of the detector on optical fibers.

All of the analog functions are performed on preamplifier daughterboards. These daughterboards, sketched in figure 14, connect directly both to the cryostat feedthrough pins, to access the input signals from the calorimeter, and also to the motherboard, for power, control, and output lines. Each barrel (endcap) motherboard contains 15 (4) daughterboards, each of which contains 48 channels of electronics, for a total of 720 (192) channels per motherboard. Four physical flanges and motherboards (3 containing preamplifiers and one conatining high voltage and instrumentation feedthroughs) make up one logical endcap tophat.

The daughterboards contain three types of custom hybrid devices: three 16-channel input protection hybrids, six 8-channel preamplifier and calibration hybrids, and three 16-channel analog storage and multiplexing hybrids called Calorimeter Data Units (CDU).[10]

Sensitive preamplifier input FETs must be protected from large current spikes due to high voltage discharges in the LAC towers or blocking capacitors. Protection is achieved in two stages of diode pairs to ground. While the second pair is integrated onto the preamplifier hybrids, the peak current and fast rise time requirements led us to package the first stage diodes in a separate custom single inline hybrid. The first stage protection diodes are designed to handle 200 Amps of current for several microseconds. Careful testing was necessary to select a high current diode with sufficiently low noise ($\sim 1000e^-$ within the system bandwidth) to avoid seriously degrading the noise performance of the preamplifiers. The diodes were manufactured by Promex Co. at a cost of approximately $20 per hybrid (16 channels).

The preamplifier hybrids contain low noise, charge sensitive amplifiers followed by pulse shaping circuits and output drivers. The preamplifier design uses a low noise FET input transistor (Hitachi 2SK190) and a feedback circuit with Radeka's "electronically cooled resistance"[11] for damping. Unipolar $4\mu s$ pulse shaping is provided by a CR high pass filter (differentiator) with pole-zero compensation. A low pass RC filter (integrater) located on the CDU hybrid completes the pulse shaping. A schematic of the preamp circuit is shown in figure 15.

The preamplifier hybrids contain a calibration charge injection circuit for each preamp channel. This circuit is located on a second hybrid substrate, packaged back-to-back with the preamplifier substrate. A shaped calibration pulse can be injected into any combination of preamplifier channels. The calibration charge consists of a reference voltage, supplied by a 12-bit 2.5 volt DAC on the controller board, switched onto an 8.4 pF calibration capacitor at the preamplifier input. The injected charge for each channel is equalized to an accuracy of 1/4 % by laser trimming the calibration capacitor. The preamp + calibration hybrids were manufactured by

Hytek Microsystems at a cost of approximately $130 per hybrid (8 channels).

The CDU hybrids are analog storage and multiplexing circuits. An input shaper / amplifier produces two outputs, at gains of x1 and x8, for each of 16 input channels. A custom integrated circuit (the CDU chip)[12] then samples the 32 analog signals in parallel at selected times, storing the amplitudes as charges on capacitors. LAC preamplifier signals are sampled twice each beam crossing — once for a baseline measurement and once at the peak of the shaped pulse. The baseline and peak sampling times are sent as "write" strobes from the controller board. The CDU also serves as a multiplexer, delivering its 64 analog outputs in a serial data stream, clocked out at 1.6 microsecond intervals by "read" strobes from the controller board. CDU hybrids were manufactured by Promex at a cost of approximately $55 per hybrid (16 channels).

Analog signals from the daughterboards are digitized on one analog-to-digital (A/D) board per tophat. The A/D board has eight parallel processing channels, each serving two daughterboards. The differential current from a CDU output is converted to a voltage, sampled and held, and digitized to 12 bits by a 3.2 μsec per conversion, low power CMOS A/D converter. A parity bit and three framing bits are added to each digitized data word for use in data checking and timing. The eight 16-bit data words from each conversion cycle are loaded in a chain of parallel/serial shift registers, which are clocked at a rate of 32 MHz by readout pulses from the controller board.

An optical driver (Hewlett Packard HFBR-1414) converts the final serial bit stream to a series of light pulses, which is sent on a 50 meter long optical fiber to a FASTBUS rack on top of the detector. Two optical drivers and output fibers are provided for each A/D board for redundancy; only one is actually read out. The transmission of optical data provides noise immunity in a compact cable.

Various parameters, such as power supply voltages and currents, daughterboard temperatures, and temperatures and liquid levels inside the liquid argon cryostat, are monitored in each tophat by a special monitoring board. Data from this "cryo" board is read out over an independent data path from the tophat, through a CAMAC data acquisition system to a dedicated microVAX. In practice, this system was used heavily only during the initial argon fill and first few months of detector operation, and could have been omitted entirely from the detector design.

(b) Front-end Electronics Performance

The front-end electronics for the LAC have been extensively tested in the lab and on the detector. Most of the performance tests use the calibration system built into the LAC preamplifiers to inject a known charge into selected electronics channels. This tests the entire electronics readout chain from preamplification through digitization and FASTBUS data acquisition. Cosmic ray tests will be discussed in a later section.

The range of expected signals in the LAC is quite large, varying from a charge of 24 fC ($1.5\ 10^5\ e^-$) for a minimum ionizing particle traversing an EM1 tower (or even less for a soft photon or electron) to approximately 17 pC ($10^8 e^-$) for a 50 GeV electromagnetic shower contained in a single EM tower. The dual gain amplification scheme in combination with 12-bit digitization gives an effective 15-bit dynamic range, allowing the full signal range to be covered with good resolution. At high gain one ADC count corresponds to an input charge of $5000e^-$, which is approximately equivalent to the rms noise on the smallest calorimeter channels.

The gain and linearity of the LAC electronics is tested by pulsing all channels repeatedly at different values of injected charge. The response of the electronics is quite linear over the entire signal range. Deviations from a straight line are less than 1% at the high end of the scale and less than 1 ADC count at the low end. Calibration data are taken regularly to relate the ADC response to injected calibration charge for every channel. The response is tabulated at 17 calibration points spanning each of the two gain ranges. Calibration constants derived from these runs are later used to correct incoming data on the fly, correcting for the small nonlinearities of the system.

The gain of the LAC electronics is fairly sensitive to temperature. The CDU, in particular, has a temperature dependent response which leads to a gain variation of $-0.3\%/^0\mathrm{C}$. The preamplifier output level also depends strongly on temperature, but the actual gain of the preamplifier is temperature independent. Output level and other similar offset variations cancel in the normal peak – baseline subtraction. Long test runs, lasting several days, initially showed slow gain variations of up to 0.6%, correlated with daily temperature swings monitored on the tophat daughterboards of up to $\pm 1.4^0$C. Regulation of the flow of tophat cooling water subsequently reduced these temperature and gain variations to less than 0.1%.

The noise level of the LAC front-end electronics is dominated by the preamplifier FET input stage. The intrinsic noise of the preamplifier (expressed as equivalent charge at the input) is $2500e^-$ in the absence of input capacitance. Digitization effects (ADC quantization) increase the actual noise of the full readout system to $4000e^-$ (0.8 ADC count) at high gain. To achieve this noise performance on the detector, careful attention to grounding was necessary. Although some ground wires are carried along with the signal wires from the calorimeter towers through the feedthroughs to the tophats, we found it necessary to provide additional grounding. Daughterboards were grounded, through the motherboard, directly to the faceplate of the LAC, which is mechanically connected to the ground plates of the calorimeter towers. With this grounding scheme, noise performance on the detector matches that achieved in the lab.

Noise in the LAC preamplifiers depends strongly on the input capacitance, increasing linearly with a slope of $2600e^-$/nF. The preamplifier pulse shaping time of $4\mu s$ was chosen to optimize the tradeoff between intrinsic noise and the noise slope for capacitances of about 1 nF typical of EM2 calorimeter towers. In the EM1 section of the calorimeter, capacitances are smaller and the intrinsic noise term dominates. Noise in hadronic towers is dominated by the capacitive term, reaching $12000e^-$ for the largest towers. Given the poorer intrinsic resolution of the calorimeter for hadron showers, this increased noise does not significantly degrade the hadronic resolution. For minimum ionizing particles, the signal to noise ratio is greater than 8:1 in all sections of the calorimeter. LAC tower capacitance ranges, noise, and signal sizes for minimum ionizing particles are collected in the following table.

Table V. Tower Capacitance, Noise, MIP signal

Layer	Capacitance (nF)	Noise (e^-)	MIP dE/dX (e^-)
EM 1	350 – 600	4000	200000
EM 2	800 – 1300	5000 – 6000	500000
HAD 1	2500 – 3700	9000 – 12000	340000
HAD 2	2700 – 3800	9000 – 12000	340000

The crosstalk of the LAC front-end electronics has been measured in the lab, using either an external pulser or the internal preamplifier calibration system to pulse one channel at a time while reading out an entire tophat. Crosstalk within a preamplifier hybrid (8 channels) is very small, roughly −0.08% from the pulsed channel to every other channel on the hybrid. The internal preamplifier calibration circuitry induces a larger crosstalk, averaging +0.3%, but only from the pulsed channel to the following channel on the hybrid. The CDU hybrid (16 channels), with its separate peak/baseline and high/low gain sampling, has a peculiar crosstalk pattern of $\sim$ 0.5% from the pulsed channel to the low gain sample of the second following channel on the hybrid. Crosstalk to more distant channels, including crosstalk from daughterboard to daughterboard, is completely negligible. The observed crosstalk patterns are simple to parametrize, and could at some stage be implemented as online corrections in the data handling code running in the FASTBUS CDMs.

Crosstalk in the actual calorimeter is dominated by capacitive coupling at the 5% level between neighboring towers. This physical crosstalk is considerably greater than any electronics crosstalk, but since it occurs only between adjacent towers, its effect on electromagnetic or hadronic showers is minimal.

(c) Fastbus Electronics

The LAC FASTBUS plant uses just three basic types of modules: one Timing and Control Module (TCM), 32 Calorimetry Data Modules (CDMs), and one "Aleph Event Builder" (AEB).

The TCM is responsible for controlling both the static and dynamic behaviour of the front-end electronics. Communications are provided by three lines: command, clock and data. These lines are used to send instructions from the TCM to the tophat controller boards in the front-end electronics. These controllers behave like state machines. At every beam crossing, the TCM sends the current mode of operation (*eg* normal running or calibration), the corresponding timing sequence (used to strobe data into the sample and hold hybrids and subsequently to clock out the digitized data), and optional instructions to change the state of various static parameters (*eg* calibration DAC settings or channel masks).

The CDMs are responsible for receiving, correcting, and storing data from the front-end electronics. Digitized data are sent on optical fibers from the front-end electronics to the CDMs. Each CDM has an associated auxiliary card mounted in the FASTBUS backplane which deserialises and demultiplexes the data for delivery to the CDM. Each CDM contains four custom chips called Digital Correction Units (DCU)[13] and four Motorola 68020 microprocessors with associated memory. Each CDM reads and processes data from two tophats.

The AEB[14] is a general purpose FASTBUS computer based on a Motorola 68020 microprocessor, built for the Aleph experiment at LEP, which coordinates the operations of the TCM and CDMs. The programmability of the AEB and CDMs results in a system capable processing data in several ways. Three basic modes will be described.

In "diagnostic" CDM mode, the DCUs pass all four data buckets (signals and baselines at x1 and x8 gain) for each channel to the CDM memory. The CDM then passes the raw data on to the AEB, which in turn forwards it to the data acquisition VAX. This provides almost transparent access to the raw data from the front-end electronics, and is used for functionality and performance tests of single tophats. Buffer size limitations prevent the whole detector from being read at once in this mode.

In "calibration" mode, known charges are injected into the preamp inputs of all channels. The front-end responses are collected and analyzed in the CDM to derive calibration constants, consisting of a 17 point linear interpolation table for every bucket of every channel in the system. The calibration constants reside in the

CDM memory. The AEB coordinates the calibration procedure, using the TCM to set run modes and DAC calibration voltages. The CDM processors perform the actual calculation of the calibration constants, and compile diagnostic information for transfer to the data acquisition VAX. Calibration of the entire LAC takes two minutes, with all channels pulsed in parallel. Calibrations are performed daily for diagnostic purposes; the stability of the system is adequate for much less frequent calibration.

In normal "data aquisition" mode, the DCU reduces the four input raw data buckets per channel to a single calibrated output. This is done by selecting the appropriate gain path, applying calibration constants to the baseline and signal buckets, and subtracting the calibrated baseline from the calibrated signal. The CDM also forms energy sums for use in the trigger decision. For triggered events, the CDM compacts the event data using layer dependent threshold cuts, and attaches a tower identification tag to each hit above threshold. The AEB coordinates the operation of the CDMs, ensuring that they deliver information belonging to the same event. The AEB also reorganizes the tower identification tags and converts the data collected from the CDMs to the proper offline format for logging.

IX. INITIAL PERFORMANCE

Cosmic Ray Tests

The LAC has been commissioned using cosmic rays. Triggers were provided by either a scintillator or an Iarocci tube mounted in the center of the detector. Some data were also taken with triggers based on signals from the Warm Iron Calorimeter (WIC) surrounding the LAC. The WIC was used to provide unambiguous muon identification and to locate muon tracks in the LAC. Some data were also taken with the Central Drift Chamber (CDC), to provide more precise tracking and to establish inter-system alignment.

The entire LAC was read out for each cosmic ray trigger. Calibration constants and a low threshold cut were applied online by the FASTBUS data acquisition system to each channel. The data analysis (and most of the event rate) was restricted to cosmic rays travelling nearly vertically downward. To select energetic muons passing through the entire detector, back-to-back hits were required in upper and lower WIC towers. Only calorimeter towers near the muon track in the lower half of the LAC were used in the analysis presented here. In each of the four longitudinal sections of the LAC, all hits in a window of 3x3 towers centered on the muon location were added together.

Pulseheight distributions in the four LAC sections are shown in figure 16. Signals are well above from noise in all layers. The pulseheight scale is proportional to the charge deposited in the liquid argon (argon/lead sampling is not included). Corrections for the high voltage blocking capacitors ($\sim 20\%$), argon charge collection efficiency ($\sim 5\%$), and the angle of incidence of the track ($\sim 5\%$) have been made. Arrows indicate the calculated mean energy loss for a minimum ionizing particle traversing the argon in each section. The data agree well with expectations.

The response of the LAC as a function of high voltage has also been studied using cosmic rays. The LAC is normally operated at 2000 volts (across liquid argon gaps of 2.75 mm); test data were taken with voltages from 3000 volts down to 250 volts. Cosmic ray signals in the LAC are shown in figure 17 as a function of voltage. The signal decreases with decreasing voltage because the electron drift path length decreases, allowing more charge to be captured by electronegative impurities, and because recombination of the liquid argon ions and electrons increases as the drift velocity decreases. The curve shows the predicted response of the LAC with 0.7 ppm of oxygen in the liquid argon. This level of contamination is consistent with independent measurements of the argon taken before filling the detector.

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REFERENCES

1. SLD Design Report, SLAC-273 (1984).
2. J.E. Brau and T.A. Gabriel, Nucl. Instr. and Meth. A279 (1989) 40.
3. Proceedings of the Workshop on Compensated Calorimetry, CALT-68-1305, Pasadena (1985).
4. R. Dubois *et al.*, IEEE Trans. Nucl. Sci. NS-33 (1986) 194.
5. C. W. Fabjan *et al.*, Phys. Lett. 60B (1975) 105;
   Nucl. Instr. and Meth. 141 (1977) 61.
6. A.C.Benvenuti *et al.*, Nucl. Instr. and Meth. A276 (1989) 94;
   A.C.Benvenuti *et al.*, Nucl. Instr. and Meth. A290 (1990) 353.
7. S.Berridge *et al.*, IEEE Trans. Nucl. Sci. 37 (1990) 1191.
8. Safety Analysis and Review for the SLD, SLAC, July 1989.
9. G.M. Haller, J.D. Fox, and S.R. Smith, IEEE Trans. Nucl. Sci. NS-36 (1989) 675;
   E. Vella, I. Abt, G.M. Haller, and A. Honma, IEEE Trans. Nucl. Sci. NS-36 (1989) 822;

— G.M. Haller, D. Nelson, and D.R. Freytag, IEEE Trans. Nucl. Sci. NS-34 (1987) 170.

10. G.M. Haller *et al.*, IEEE Trans Nucl Sci NS-35 (1988) 217.

11. V. Radeka, IEEE Trans. Nucl. Sci. NS-21 (1974) 51.

12. G.M. Haller *et al.*, IEEE Trans. Nucl. Sci. NS-33 (1986) 221.

13. MacKenzie *et al.*, IEEE Trans. Nucl. Sci. NS-34 (1987) 250.

14. A. Marchioro *et al.*, IEEE Trans. Nucl. Sci. NS-34, (1987) 133.

FIGURE CAPTIONS

1) Quadrant drawing of SLD detector, showing position of barrel and endcap LAC. Dashed lines indicate the projective LAC towers.

2) Barrel LAC module and cryostat assembly.

3) Endcap LAC module and cryostat assembly.

4) Barrel LAC electromagnetic (EM) and hadronic (HAD) modules.

5) Endcap LAC module.

6) Calorimeter tile and spacer detail (section of a hadronic module).

7) Signal Highway PC Board circuit, providing high voltage to calorimeter towers and coupling signals from the towers to the external electronics.

8) LAC cabling from towers through flanges to front-end electronics. Feedthrough patterns on cold and warm flanges are also shown.

9) Cross-section of a liquid argon high voltage feedthrough.

10) LAC cryogenic system schematic, showing main argon, nitrogen, and vacuum lines.

11) LAC electronics organizational scheme. The front-end electronics, mounted in "tophats" connected directly to flanges on the detector, perform all analog signal processing. Digitized data are sent to FASTBUS modules on top of the detector for further processing.

12) Tophat electronics organizational chart, showing the hierarchy of signal processing boards and custom hybrid circuits within a tophat.

13) Tophat signal processing electronics. Functional diagram of the analog signal processing performed in the custom hybrid circuits contained within a daughterboard, and the digitization performed within an A/D board.

14) LAC daughterboard. Preamplifier hybrids are mounted on both sides. The daughterboard plugs into both the detector and the tophat motherboard.

15) LAC preamplifier circuit diagram.

16) Cosmic ray pulseheight distributions in the four LAC sections. Arrows indicate predicted mean (not peak) signals for minimum ionization in liquid argon.

17) Cosmic ray signal in LAC as a function of voltage. Pulseheights from all layers are added, with no weighting for argon/lead sampling. Curve is predicted response for minimum ionization in argon with 0.7 ppm oxygen.

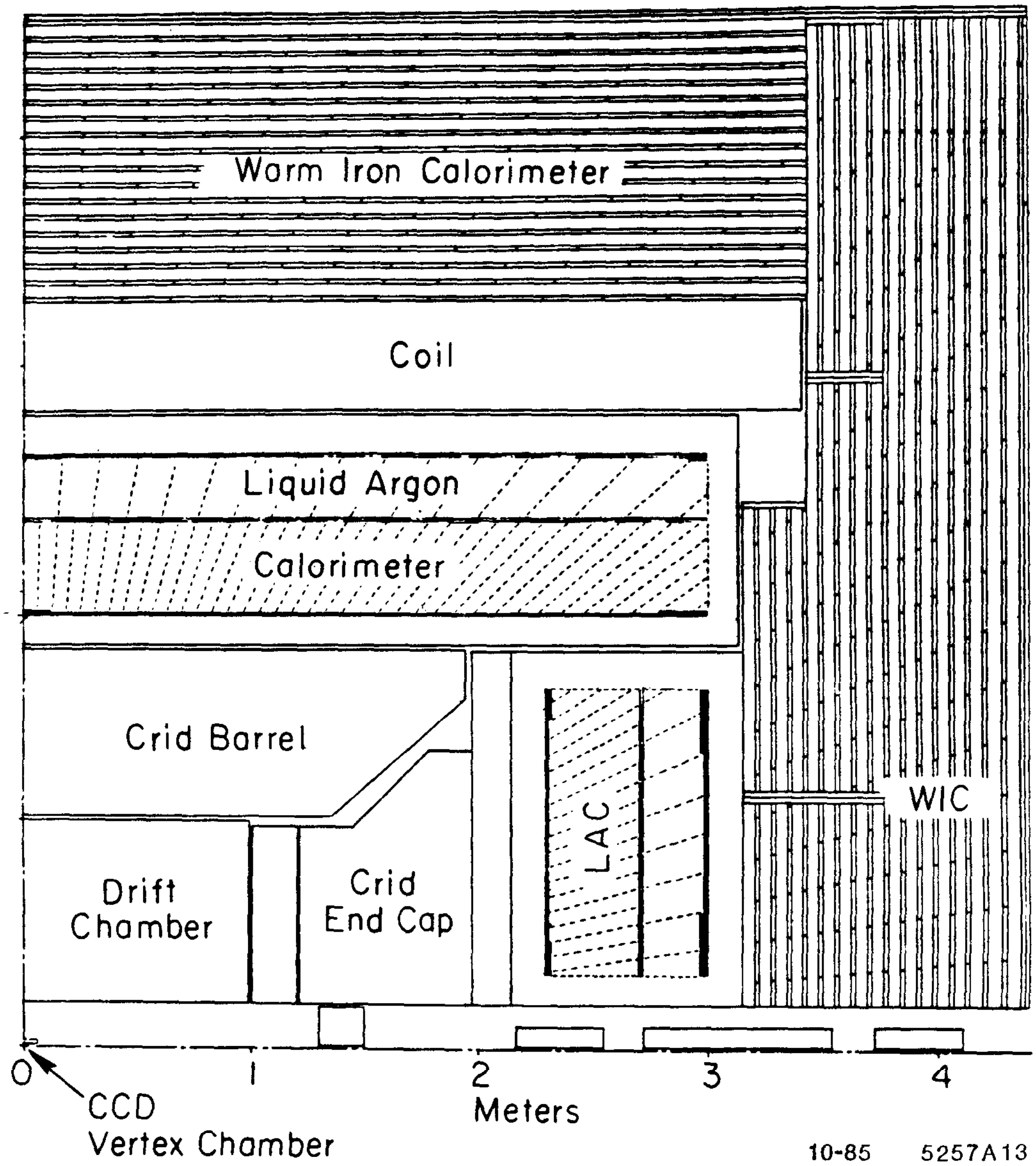

Warm Iron Calorimeter
Coil
Liquid Argon
Calorimeter
Crid Barrel
WIC
LAC
Drift Chamber
Crid End Cap
0
1
2
3
4
Meters
CCD Vertex Chamber
10-85 5257A13

Fig. 1

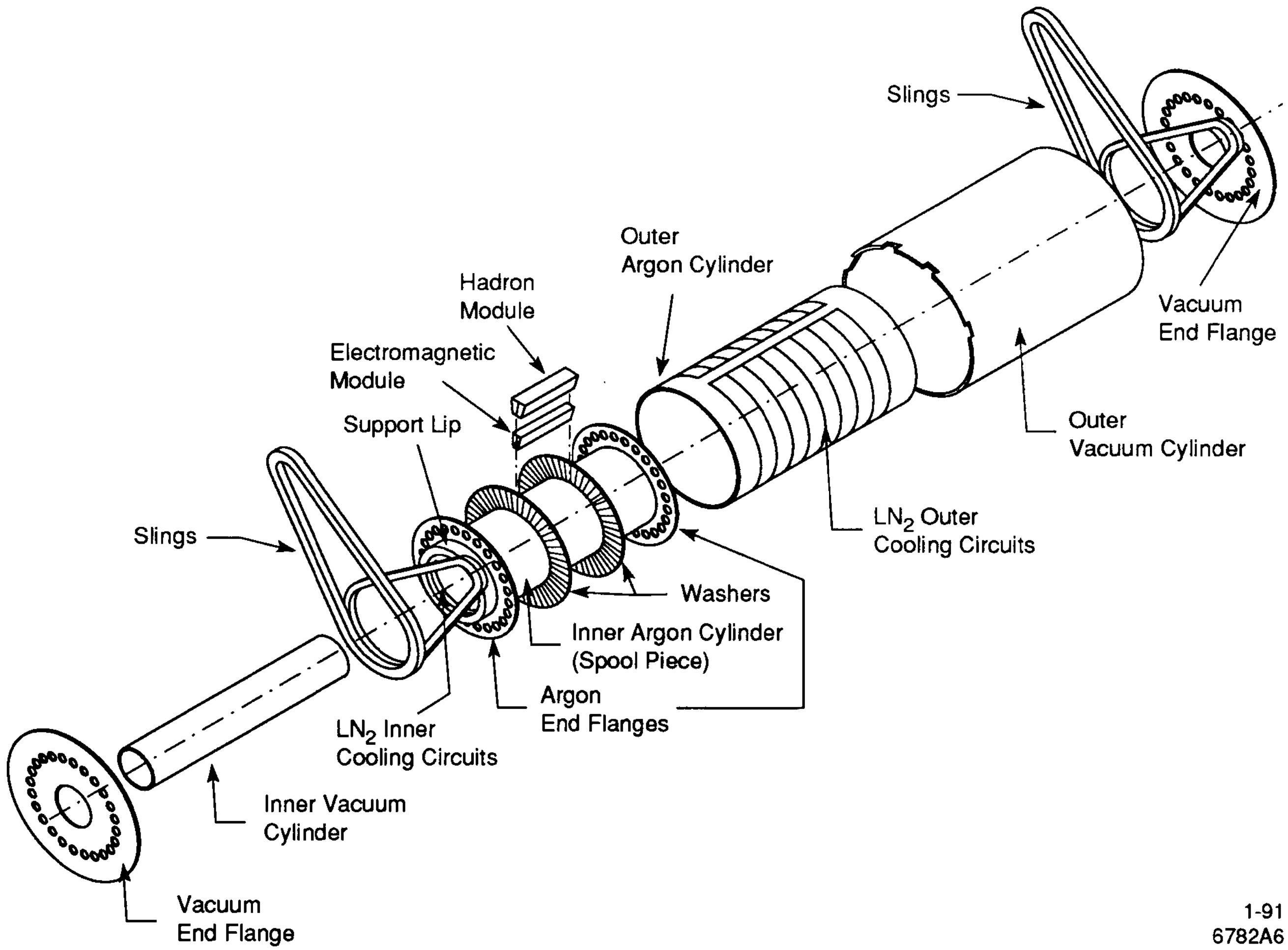

Slings
Vacuum
End Flange
Outer
Argon Cylinder
Hadron
Module
Electromagnetic
Module
Support Lip
Outer
Vacuum Cylinder
LN_2 Outer
Cooling Circuits
Slings
Washers
Inner Argon Cylinder
(Spool Piece)
Argon
End Flanges
LN_2 Inner
Cooling Circuits
Inner Vacuum
Cylinder
Vacuum
End Flange
1-91
6782A6

Fig. 2

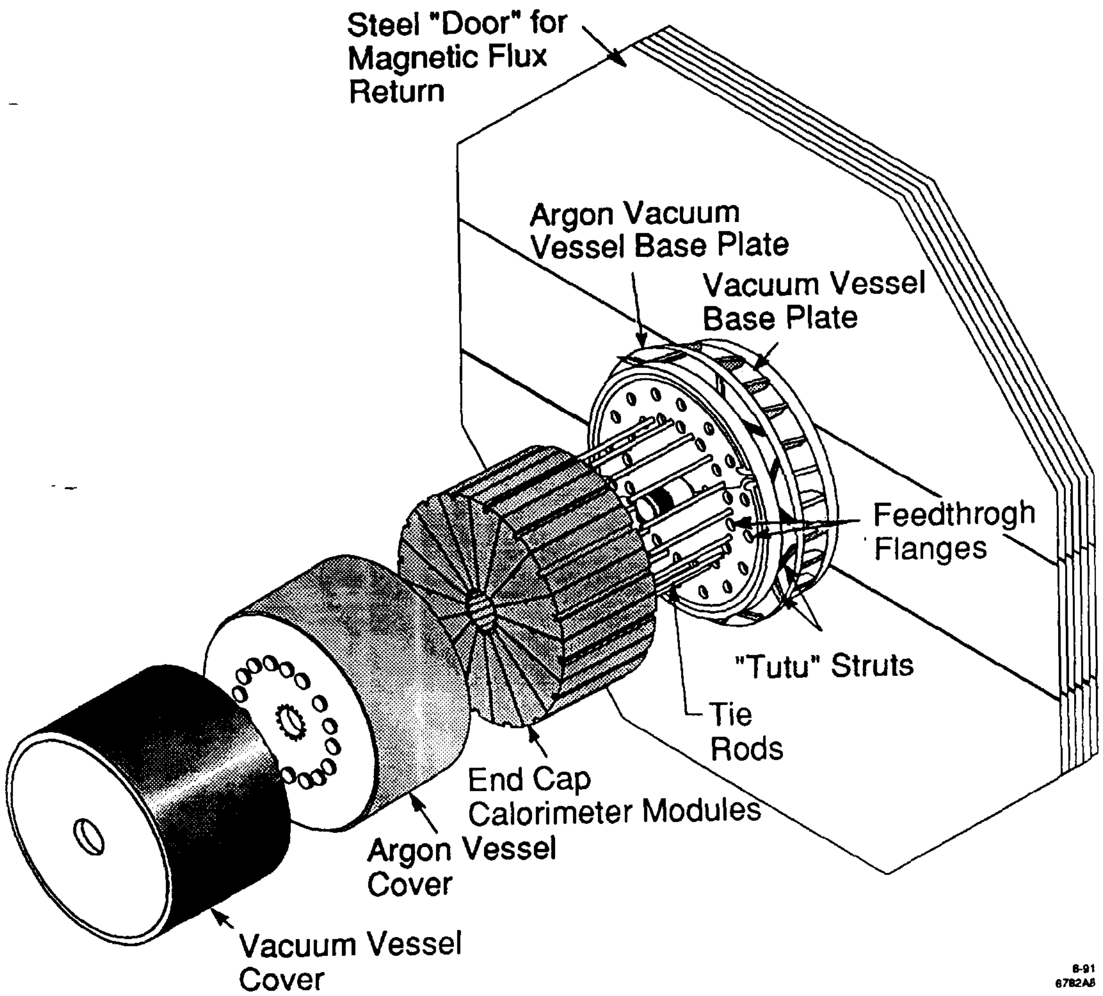

Steel "Door" for
Magnetic Flux
Return
Argon Vacuum
Vessel Base Plate
Vacuum Vessel
Base Plate
Feedthrogh
Flanges
"Tutu" Struts
Tie
Rods
End Cap
Calorimeter Modules
Argon Vessel
Cover
Vacuum Vessel
Cover
8-91
6782A8

Fig. 3

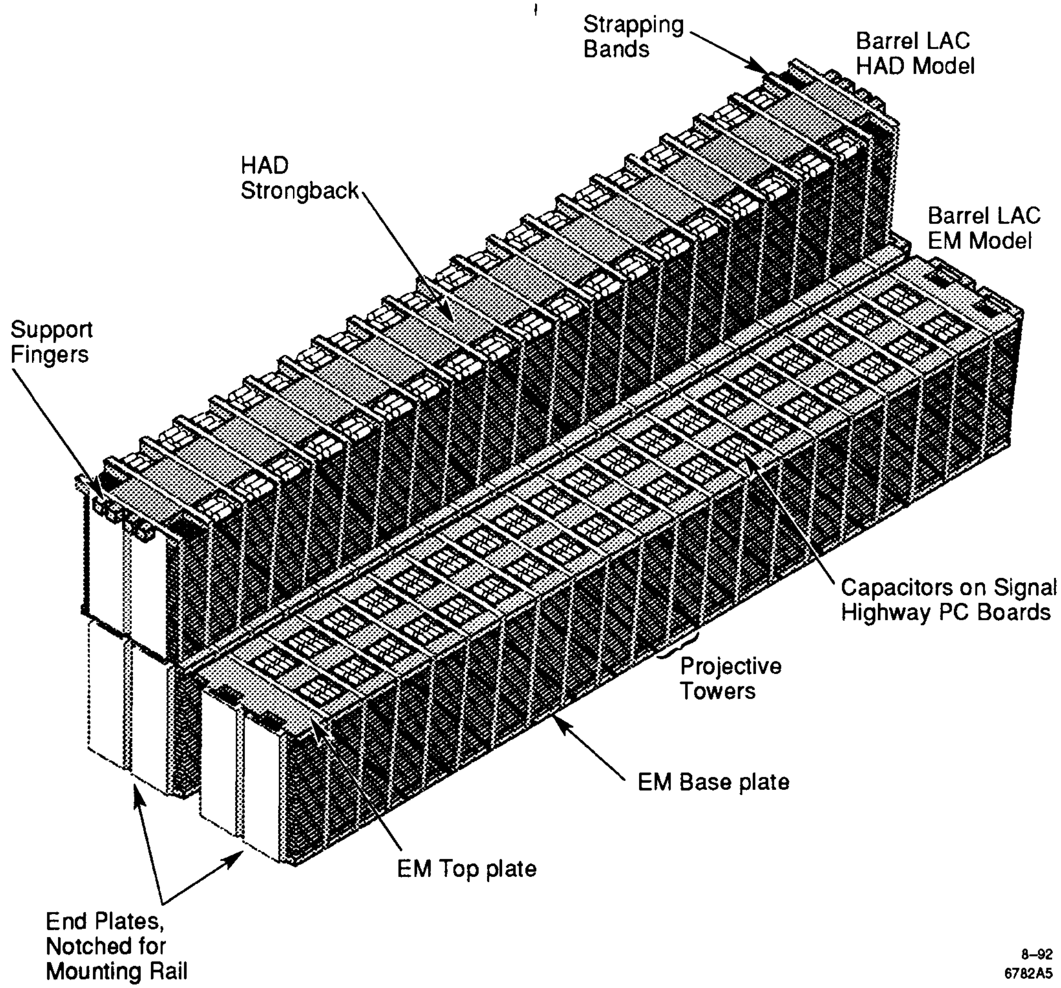
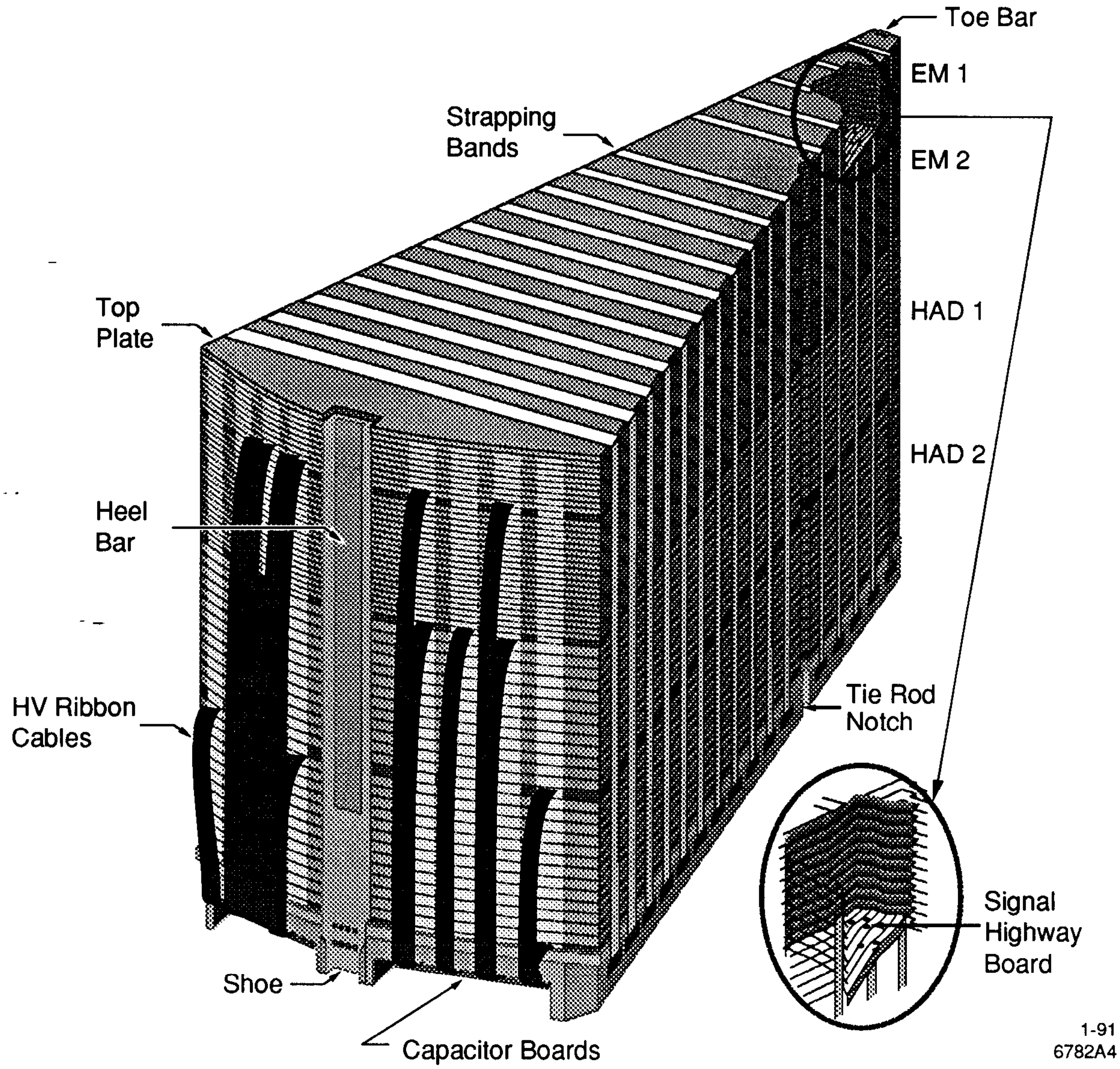

Strapping
Bands
Barrel LAC
HAD Model
HAD
Strongback
Barrel LAC
EM Model
Support
Fingers
Capacitors on Signal
Highway PC Boards
Projective
Towers
EM Base plate
EM Top plate
End Plates,
Notched for
Mounting Rail
8–92
6782A5

Fig. 4



Toe Bar
EM 1
EM 2
Strapping
Bands
HAD 1
HAD 2
Top
Plate
Heel
Bar
HV Ribbon
Cables
Tie Rod
Notch
Signal
Highway
Board
Shoe
Capacitor Boards
1-91
6782A4

Fig. 5

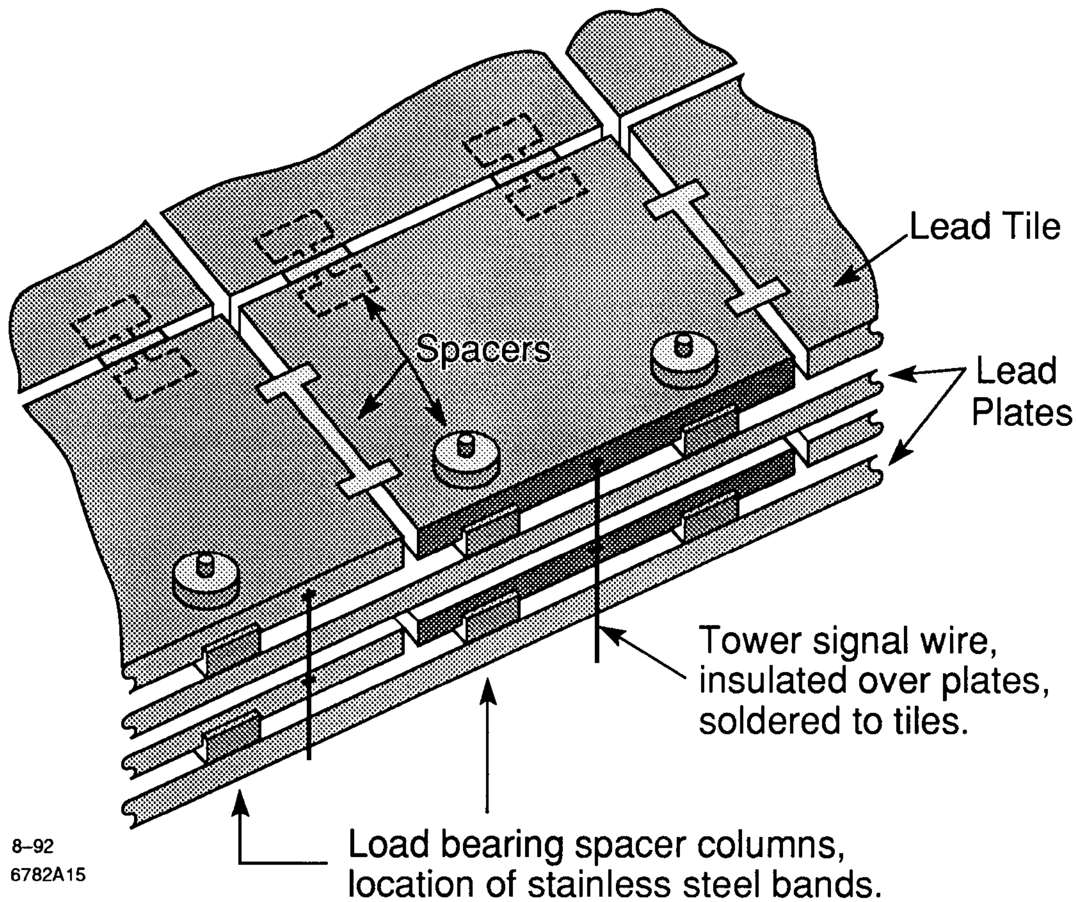

Lead Tile
Spacers
Lead
Plates
Tower signal wire,
insulated over plates,
soldered to tiles.
Load bearing spacer columns,
location of stainless steel bands.
8–92
6782A15

Fig. 6

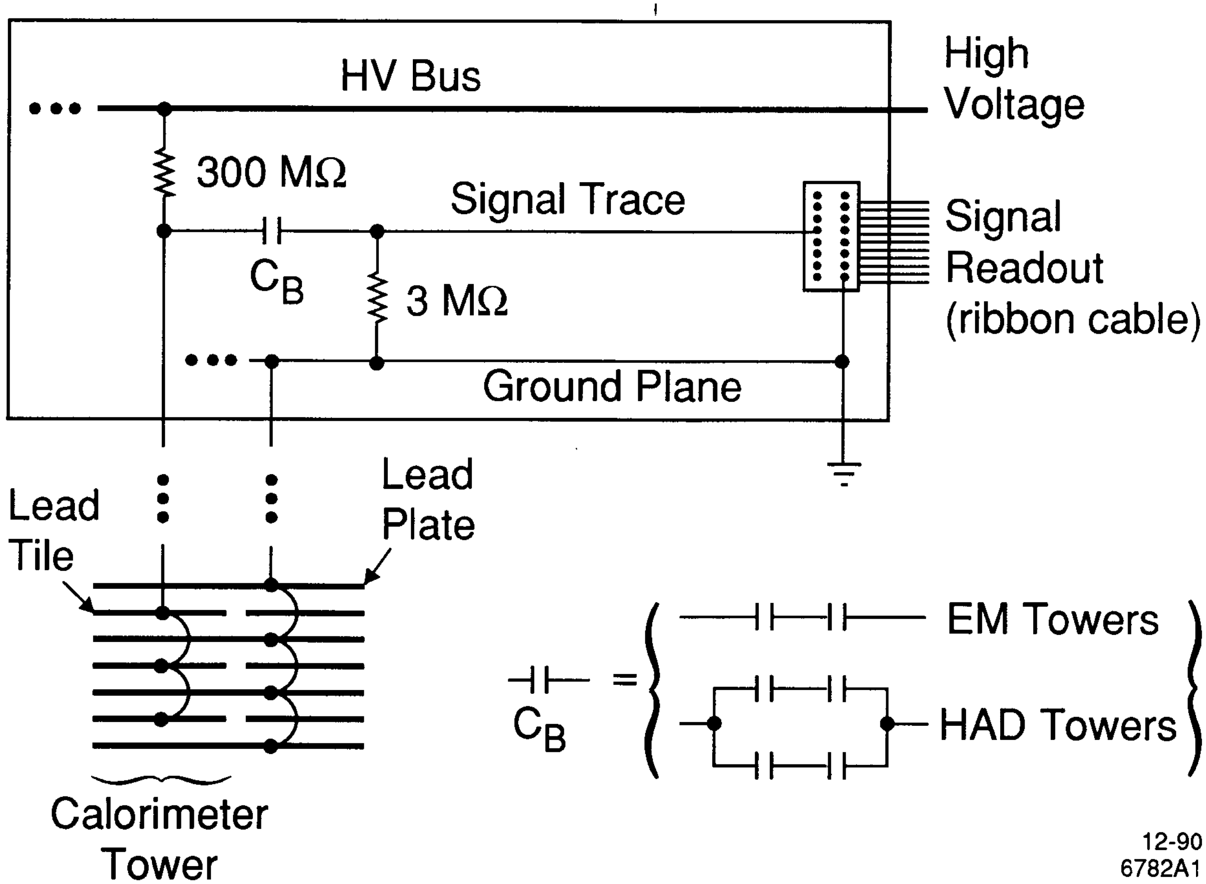
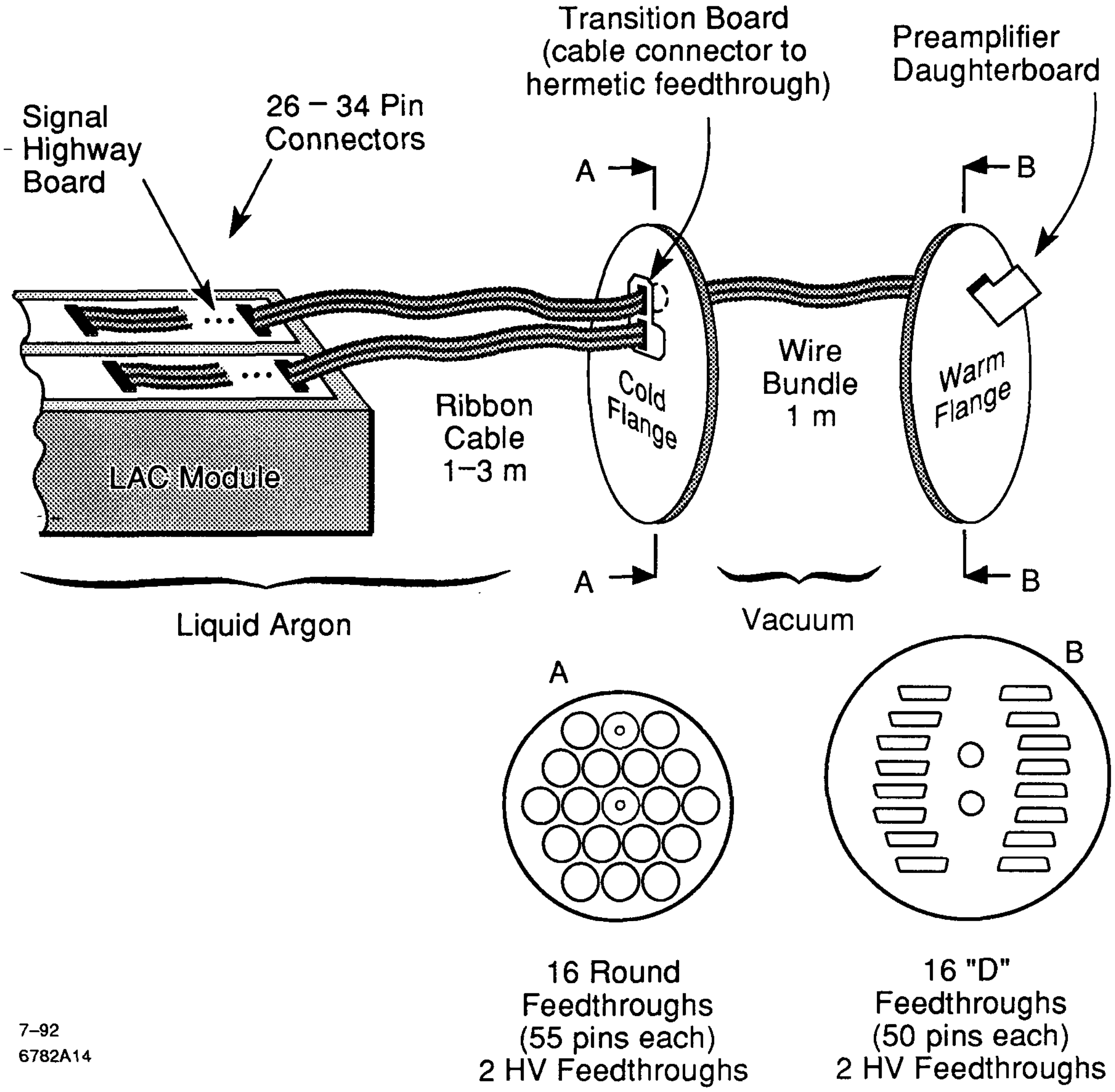

HV Bus
High
Voltage
300 MΩ
Signal Trace
Signal
Readout
(ribbon cable)
C_B
3 MΩ
Ground Plane
Lead
Tile
Lead
Plate
Calorimeter
Tower
C_B =
EM Towers
HAD Towers
12-90
6782A1

Fig. 7



Transition Board
(cable connector to
hermetic feedthrough)
Preamplifier
Daughterboard
Signal
Highway
Board
26 – 34 Pin
Connectors
A
B
LAC Module
Ribbon
Cable
1–3 m
Cold
Flange
Wire
Bundle
1 m
Warm
Flange
A
B
Liquid Argon
Vacuum
A
B
16 Round
Feedthroughs
(55 pins each)
2 HV Feedthroughs
16 "D"
Feedthroughs
(50 pins each)
2 HV Feedthroughs
7–92
6782A14

Fig. 8

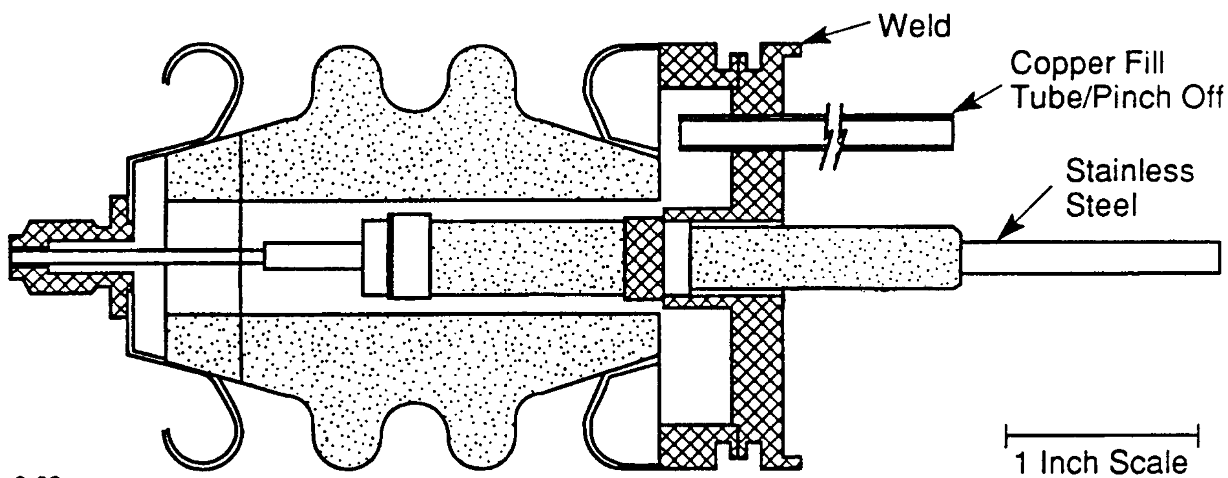
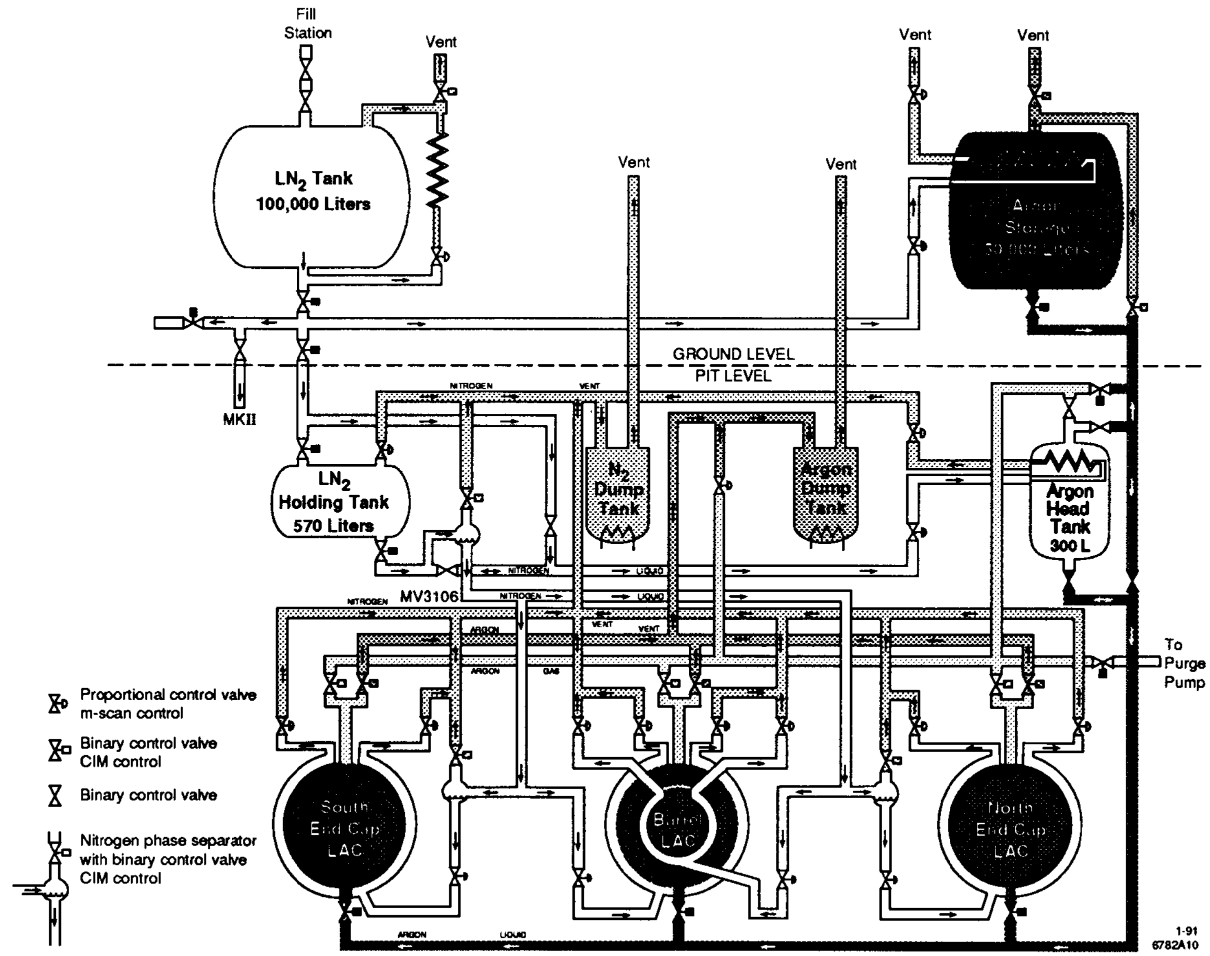
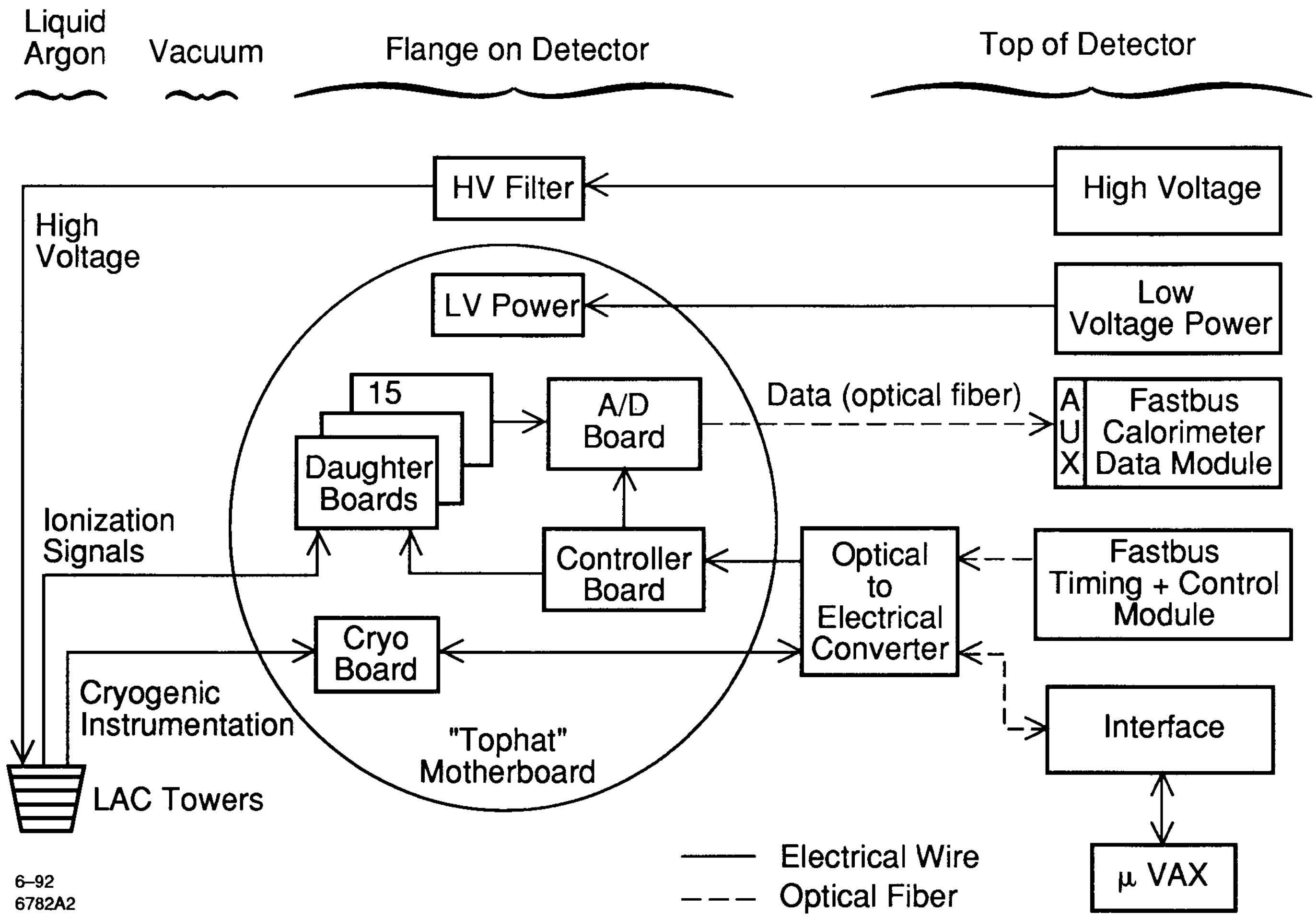

Weld
Copper Fill
Tube/Pinch Off
Stainless
Steel
1 Inch Scale
9-92
6782A21

Fig. 9



Fill Station
Vent
LN2 Tank
100,000 Liters
Vent
Vent
Vent
Vent
MKII
GROUND LEVEL
PIT LEVEL
LN2
Holding Tank
570 Liters
N2
Dump
Tank
Argon
Dump
Tank
Argon
Head
Tank
300 L
MV3106
To
Purge
Pump
Proportional control valve
m-scan control
Binary control valve
CIM control
Binary control valve
Nitrogen phase separator
with binary control valve
CIM control
South
End Cap
LAC
Barrel
LAC
North
End Cap
LAC
1-91
6782A10

Fig. 10



Liquid Argon
Vacuum
Flange on Detector
Top of Detector
HV Filter
High Voltage
High Voltage
LV Power
Low Voltage Power
15
Daughter Boards
A/D Board
Data (optical fiber)
A U X
Fastbus Calorimeter Data Module
Ionization Signals
Controller Board
Optical to Electrical Converter
Fastbus Timing + Control Module
Cryo Board
Cryogenic Instrumentation
"Tophat" Motherboard
Interface
LAC Towers
Electrical Wire
Optical Fiber
μ VAX
6–92
6782A2

Fig. 11

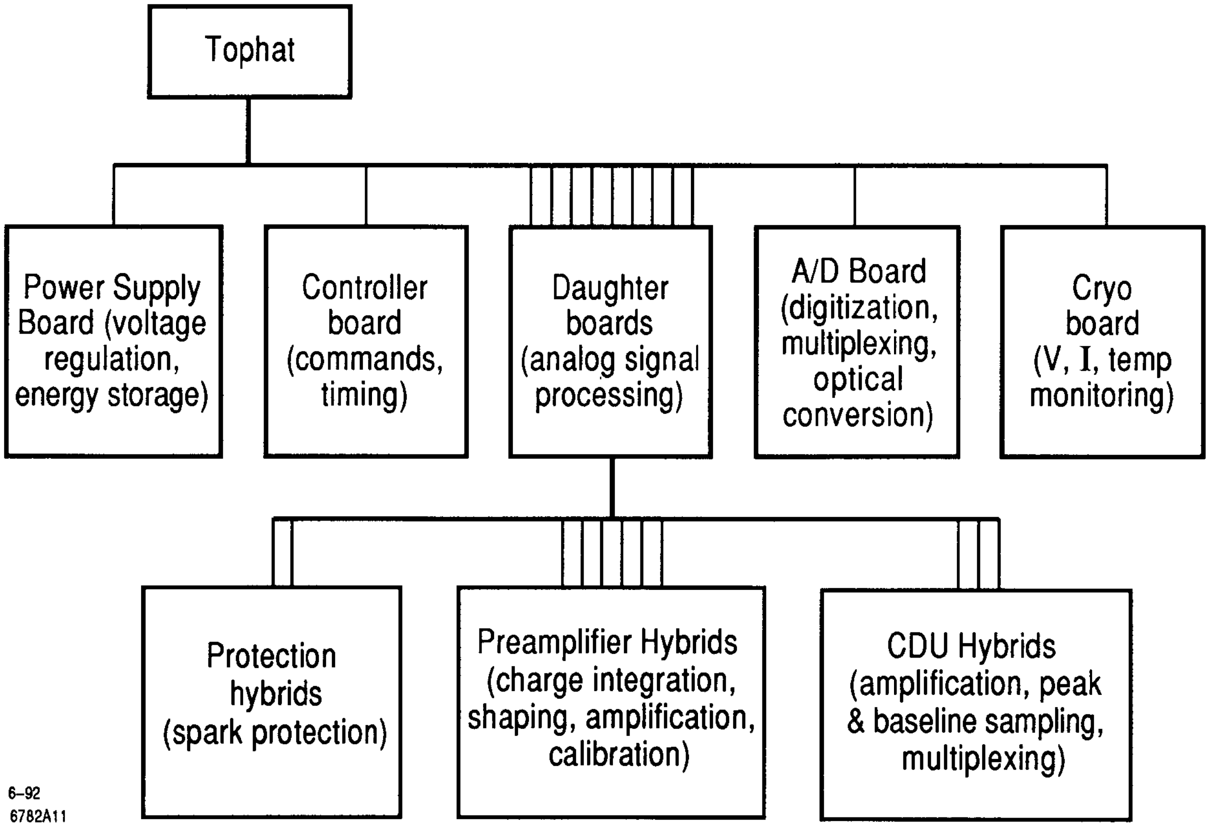

Tophat
Power Supply Board (voltage regulation, energy storage)
Controller board (commands, timing)
Daughter boards (analog signal processing)
A/D Board (digitization, multiplexing, optical conversion)
Cryo board (V, I, temp monitoring)
Protection hybrids (spark protection)
Preamplifier Hybrids (charge integration, shaping, amplification, calibration)
CDU Hybrids (amplification, peak & baseline sampling, multiplexing)
6–92
6782A11

Fig. 12

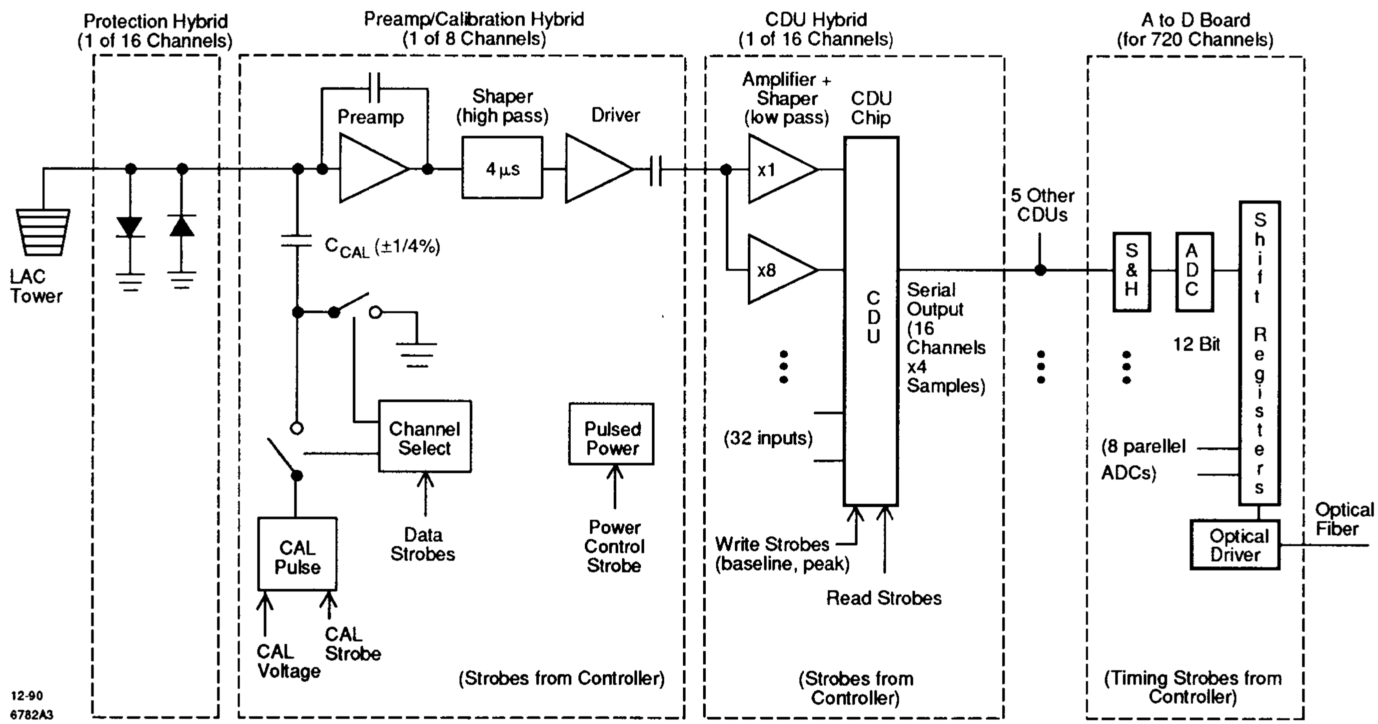

Protection Hybrid
(1 of 16 Channels)
Preamp/Calibration Hybrid
(1 of 8 Channels)
CDU Hybrid
(1 of 16 Channels)
A to D Board
(for 720 Channels)
Preamp
Shaper
(high pass)
Driver
4 µs
Amplifier +
Shaper
(low pass)
CDU
Chip
x1
x8
C
D
U
LAC
Tower
CCAL (±1/4%)
Channel
Select
Pulsed
Power
CAL
Pulse
Data
Strobes
Power
Control
Strobe
CAL
Voltage
CAL
Strobe
(Strobes from Controller)
(32 inputs)
Write Strobes
(baseline, peak)
Read Strobes
(Strobes from
Controller)
Serial
Output
(16
Channels
x4
Samples)
5 Other
CDUs
S
&
H
A
D
C
12 Bit
Shift Registers
(8 parellel
ADCs)
Optical
Driver
Optical
Fiber
(Timing Strobes from
Controller)
12-90
6782A3

Fig. 13

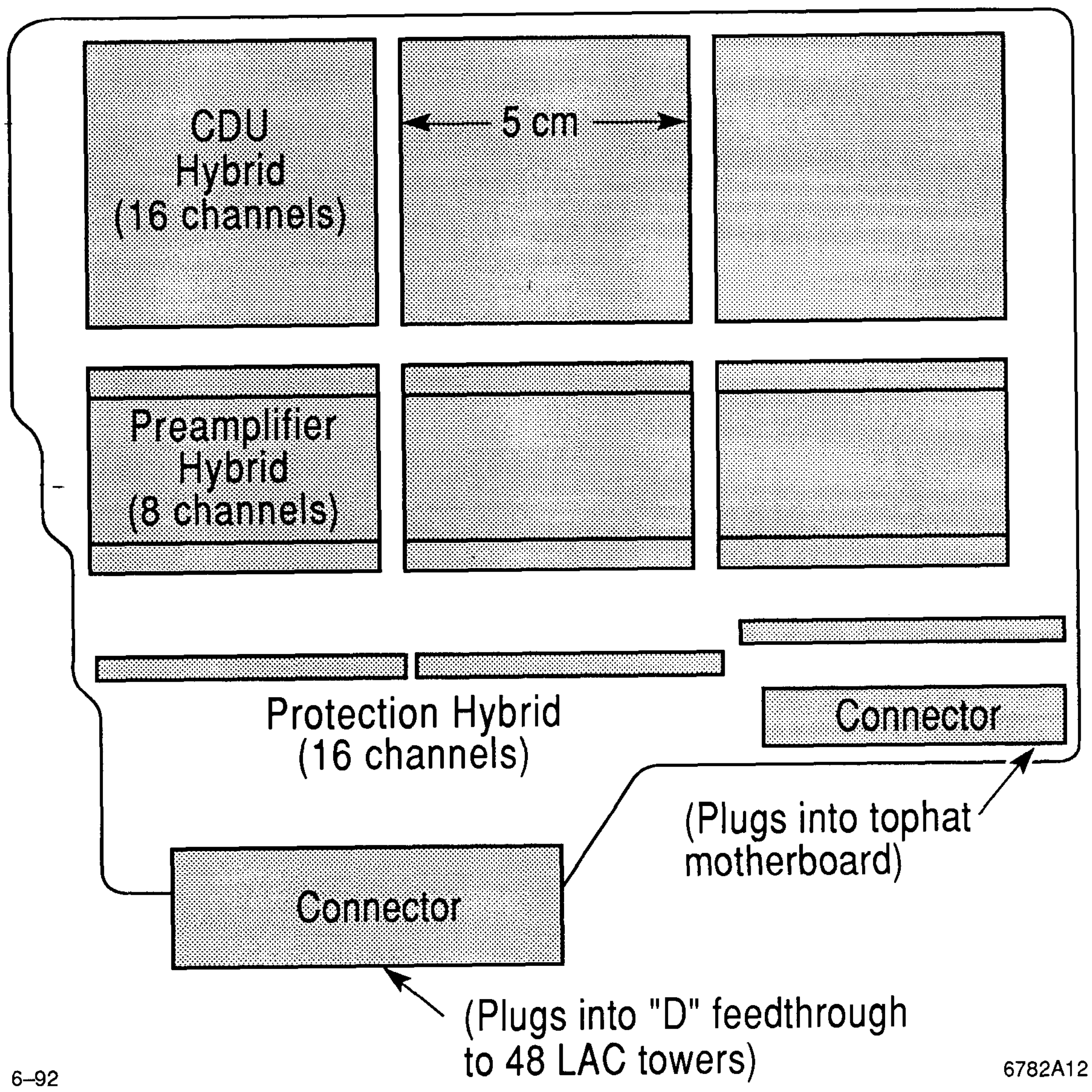

CDU
Hybrid
(16 channels)
5 cm
Preamplifier
Hybrid
(8 channels)
Protection Hybrid
(16 channels)
Connector
(Plugs into tophat
motherboard)
Connector
(Plugs into "D" feedthrough
to 48 LAC towers)
6–92
6782A12

Fig. 14

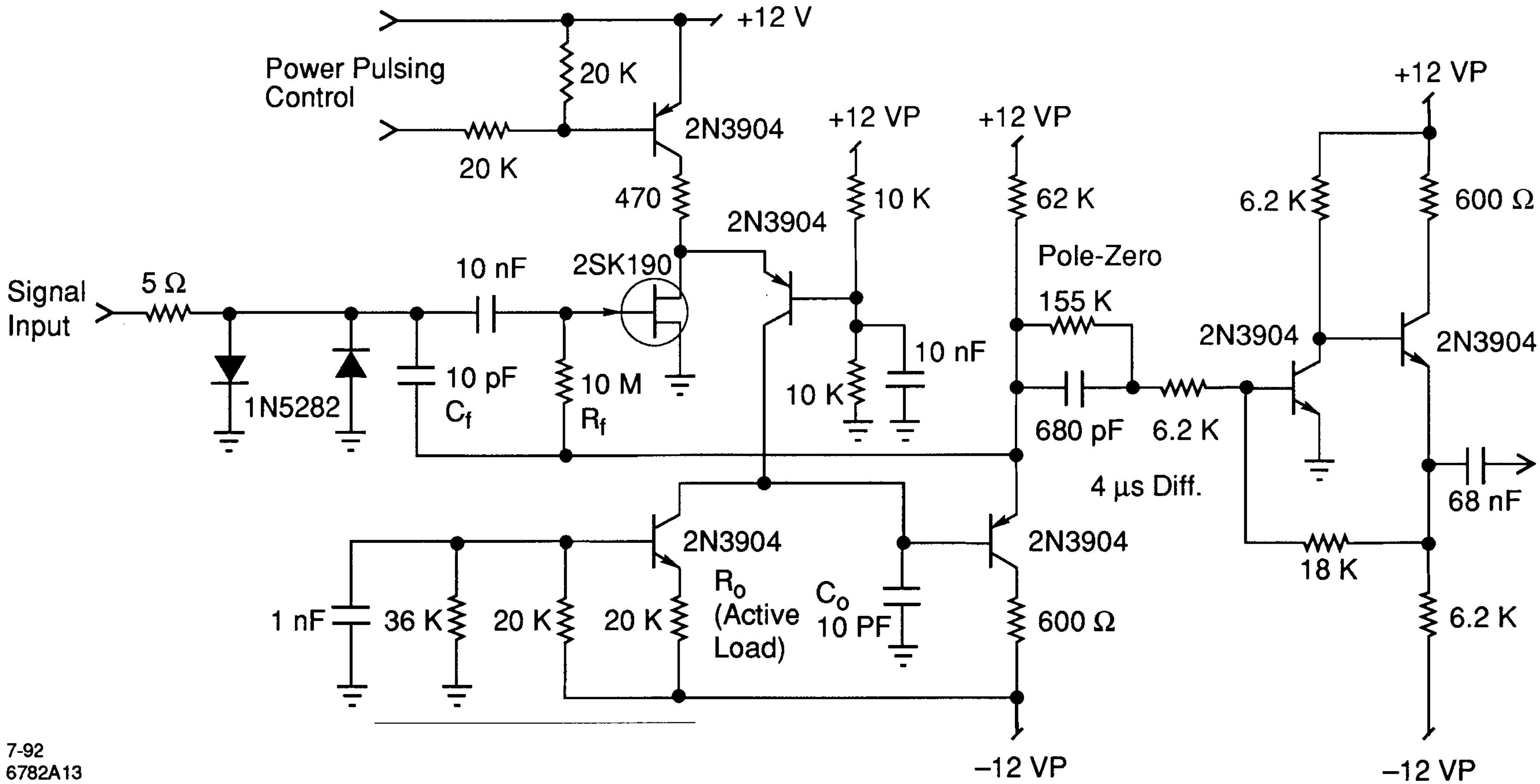

+12 V
Power Pulsing
Control
20 K
20 K
2N3904
470
2N3904
+12 VP
10 K
+12 VP
62 K
+12 VP
6.2 K
600 Ω
Signal
Input
5 Ω
10 nF
2SK190
Pole-Zero
155 K
2N3904
2N3904
1N5282
10 pF
C_f
10 M
R_f
10 K
10 nF
680 pF
6.2 K
4 µs Diff.
68 nF
2N3904
2N3904
1 nF
36 K
20 K
20 K
R_o
(Active
Load)
C_o
10 PF
600 Ω
18 K
6.2 K
–12 VP
–12 VP
7-92
6782A13

Fig. 15

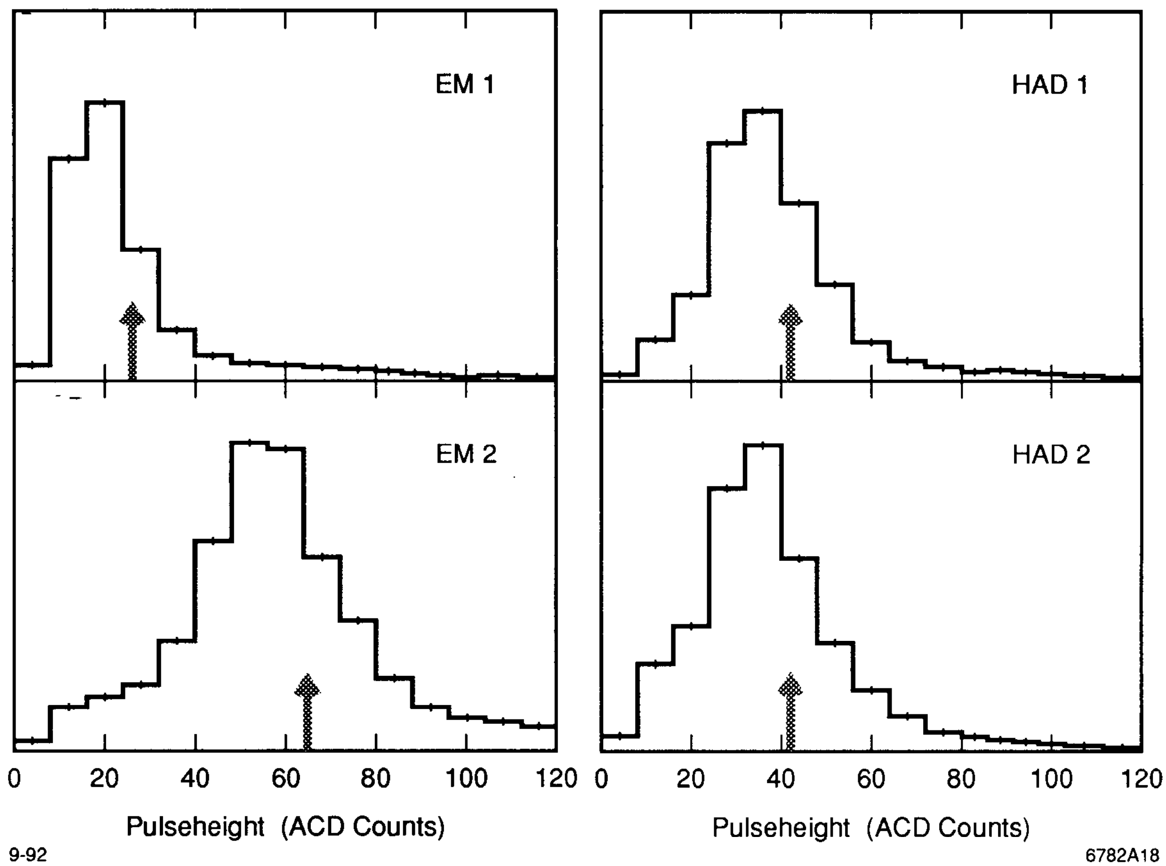
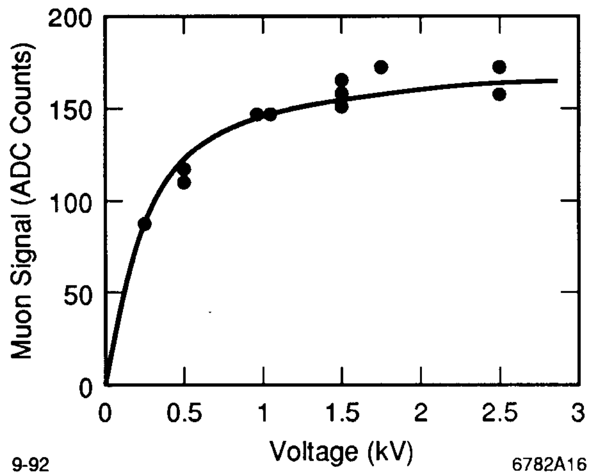

EM 1
HAD 1
EM 2
HAD 2
0
20
40
60
80
100
120
0
20
40
60
80
100
120
Pulseheight (ACD Counts)
Pulseheight (ACD Counts)
9-92
6782A18

Fig. 16



Muon Signal (ADC Counts)
200
150
100
50
0
0
0.5
1
1.5
2
2.5
3
Voltage (kV)
9-92
6782A16

Fig. 17