EM Electrode Design

Abstract

The EM signal electrode is a three layer flexible kapton printed circuit board. Electrical connections to the inner signal layer are made at the ends of the board through exposed via's. The outer layers are high voltage electrodes. Series resistors are silk screened along the length of the high voltage electrodes to limit the current in case of an electrical discharge and to provide electrical isolation should a high voltage electrode be shorted to ground. The electrical signal collected in the gap, defined by the absorber and the outer layers of the signal electrode, is capacitively coupled to the inner signal layer. The coupling capacitor is the parallel capacitance between the signal layer and the high voltage electrode, where kapton is the dielectric material. A detailed explanation of the electrical considerations and electronic design specifications and fabrication techniques follows. These include the requirements for a uniform electrical field, crosstalk between signal strips, the resistance value for the series high voltage resistors, charge buildup , panel size and production methods.

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December 16, 1992

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1. Accordion Structure

1.1. Basic cell

1.1.1. The electromagnetic portion of the GEM calorimeter employs an accordion electrode structure in both barrel and end cap regions. The barrel accordion electrode structure is shown in figure 1. A basic cell, figures 2 and 3, consists of an absorber plate, a liquid krypton gap, a signal electrode and another liquid krypton gap. The signal electrode is a three layer kapton printed circuit board although other polyimide materials are under consideration. Signal collection occurs on the outer layers, which are at a high voltage potential. These signals are capacitively coupled to the inner layer of the electrode. Equal sampling in the accordion structure as a function of radius is achieved by varying the bend angle as well as the exact length of the arm between bends. Figure 4 shows an assembled mini module. The endcap EM structure is built of an accordion projective structure, that because of space considerations has a flat front face. See figures 5 and 6.

1.2. Geometrical Towers

1.2.1. The transverse granularity of the accordion calorimeter is determined in the ϕ direction by the number of accordion cells summed in a readout channel, and in the η direction by the readout pattern of the signal electrodes. For the GEM calorimeter, we intend to sum four cells in ϕ and to keep the segmentation in η constant in the barrel region. This leads to towers covering an area of $\Delta\eta \times \Delta\phi$ = 0.027 x 0.027. The resulting structure has 240 towers in ϕ which require 960 absorber plates and signal electrodes. The individual EM towers will be grouped in 6 X 6 arrays for trigger purposes. Figures 7 and 8 are conceptual drawings of the tower structure.

1.3. Depth

1.3.1. The total depth of the EM calorimeter was determined by optimizing the space available, and is consistent with obtaining a good energy resolution at 50 GeV / c. The total interaction length at $\eta = 0$ is 25 *Xo* in the barrel and increasing to 28 Xo in the end caps.

1.4. Longitudinal Subdivision

1.4.1. Our desire to optimize *e* identification and π rejection and to achieve the best possible pointing back to the vertex of the electromagnetic shower determines the longitudinal subdivision of the calorimeter. The division selected was 4 *Xo* in the front section, 1.4.2. *Xo* in the middle section and 13 *Xo* in the back section, for a total interaction length of 25 *Xo* at $\eta = 0$. This increases as $1 / \sin\theta$ with increasing angle. See figure 9.

2. Trade Studies

2.1. The GEM electromagnetic accordion design requires the fabrication of multilayer flexible printed circuit boards four meters in length. This is a formidable undertaking. In its proof of principle EM calorimeter, tested this year, Brookhaven engineers have developed several techniques and methods that are applicable to the fabrication of large multilayer printed circuit boards. We feel confident that we can manufacture prototype boards to the required GEM specifications, but the techniques are labor intensive and do not take advantage of many of the procedure's and equipment used in industry. It is to our advantage to have a clear and well reasoned fabrication procedure for the flexible printed circuit boards required *before* final design begins. i.e. we must be certain that industry can successfully build at a reasonable price what we design. To this end, Brookhaven proposes to hire an outside consultant to advise us on current industrial techniques, procedures, materials and equipment available. This should help us to successfully complete this project within the time frame and cost allotted.

3. Material Specifications

3.1. Types of Kapton

3.1.1. We have been looking into two kapton products, one manufactured by Du Pont de Nemours Electronics Division, and another type sold through Shelldahl Corp. Du Pont sells two versions, type HA and type HN. Type HA has better thermal setting properties than type HN. The Shelldahl product is also a thermal

setting polyimide material and sets at a lower temperature than the Du Pont product. For this reason, and because they manufacture a lower curing temperature polyimide adhesive, we are focusing onto the Shelldahl product line.

3.2. Adhesive

3.2.1. Most manufacturers of flexible printed circuit boards use an acrylic adhesive to laminate the constituent layers together. A primary concern for this type of adhesive material is its susceptibility to radiation damage. A better choice of adhesive material would be a polyimide adhesive which has a similar composition to the kapton dielectric material used in the signal electrodes. We know of three manufactures of such materials. Two of these companies are located in the US. The first manufacturer, Du Pont de Nemours has developed a radiation hard adhesive whose primary use is in super conducting magnets. The product is available pre-applied to kapton in roll form or in sheet form. The problem with this material is its curing temperature, approximately 300 degree centigrade. Because we want to thermal set the adhesive in the mold, this will help preserve the bends, we must design a mold that operates at a much higher temperature than otherwise required. Shelldahl Corp. manufactures a polyimide adhesive with a curing temperature of only 175 degree centigrade. This lower curing temperature is extremely desirable and for that reason we have decided to pursue further this product.

3.3. Panel Size

3.3.1. Standard panel size for printed circuit manufacturers is usually 18 inch X 18 inch or 24 inch X 24 inch. The industry in general does not support larger panel sizes. The problem for multilayer printed circuit boards is with the press size, the size of the chemical baths, and the ability to produce artwork accurately over large areas. The critical dimension for the signal electrodes is its length, approximately four meters. This is further complicated by the requirement to have connections to internal layers along this dimension. Fortunately a mature industry has developed over the years which may be applicable to our needs. This is the flexible printed circuit industry. Figure 10 is an outline drawing of a kapton signal electrode.

4. Flexible Printed Circuits

4.1. A Primer

4.1.1. Understand first, that the equipment used in this industry is completely different from the equipment used in standard printed circuit technology. Standard equipment cannot simply be modified, it must be replaced with equipment designed to process materials on rolls hundreds of meters in length.

4.1.2. The first procedure is to attach the conductive material to the kapton. Two methods are utilized. The first technique uses an adhesive as the bonding agent and roller lamination methods to attach copper foil. The adhesive must be robust and resistant to the radiation damage expected in the GEM environment. A discussion of adhesives precedes this section. The second technique for bonding the conductor to the dielectric material, is to vacuum deposition a few angstroms of a conductive material directly onto the dielectric material. Additional material is plated up to the required thickness using traditional plating techniques. This method requires no adhesive and provides a much more robust adhesion to the dielectric material used.

4.1.3. Once the conductive material has been bonded to its dielectric base (lets assume that we have bonded copper to a kapton dielectric) the roll is run through an indexing machine. This machine punches precisely positioned indexing holes along the length of the kapton roll. The index holes usually run along the sides and are positioned approximately one meter apart. The exact pitch is determined by the processing equipment which follows. We now have a method to perform precise registration between layers or to return to a particular section over and over again to perform multiple tasks.

4.1.4. The next step is to lay down a film mask which is an image of the circuitry required. This is usually silked screen onto the copper with an automated silk screening machine. The panel size of most large automated machines is about a meter on a side. This means that for our four meter long board we will need four masks for each layer. Running the kapton roll through the automatic screening equipment will require four passes. The first pass will screen panels one, five etc. The second pass (after a change of masks) will screen panels two, six, etc. The registration is determined precisely by the indexing

holes. All of the chemistry used in normal printed circuit technology is applicable at this time. The panels are etched, drilled and sent to a roller laminator. Here again we rely on the indexing holes to register the individual layers to be laminated. The adhesive can be in sheet form or applied as a liquid. Again, the adhesive used must be able to survive the expected radiation environment anticipated at the SSC, and not contain impurities that would poison the krypton / argon ionizing liquid.

4.1.5. Finally, through plating techniques using exposed via's are used to inter-connect the various layers, and the outer layers are processed using standard chemistry and methods.

4.2. Conductive Inks

4.2.1. A concern with through plating technology, is the large number of operations required. Conductive inks provide a less expensive alternative. Using conductive ink eliminates the need to apply copper, or other conductive materials, to the dielectric material and then the subsequent use of baths to selectively remove or add conductive material to produce the desired image or inter-connect. At least one company that we know of is using conductive inks to inter-connect constituent layers via exposed via's. This eliminates an expensive through plating technology.

4.2.2. Conductive inks could also be used to replace the copper on inner and outer layers. There are two concerns with this approach. The first is the cost of the conductive ink. Inks with high conductivity usually require a large amount of silver as an additive. For large surface areas, this increases the cost substantially. Fortunately, the signal electrodes proposed for the GEM calorimeter require only a moderately low resistance conductive ink, (not as low as most conductive inks.) This allows us to use less silver as an additive. Also, a new product line of conductive inks is now available which uses micro spheres coated with silver. This reduces the cost of the ink further.

4.2.3. A second problem with the use of conductive inks is the inability to solder to this surface. Until recently this has been a major drawback. The use of surface mounting technology has changed al of that. Today, anisotropic films provide the adhesion and the electrical connection to these conductive inks. One can also use conductive epoxy preforms in the shape of a donut or other configuration to attach standard components to conductive ink traces. With a donut preform, these little disc's are placed over each

pin and then cured at an elevated temperature. A precise amount of conductive epoxy is applies to the connection.

4.2.4. It is our belief that the use of conductive inks to replace plated through holes and copper traces is a viable alternative to existing technologies and we plan to explore this technique further.

4.3. Resistive Ink

4.3.1. Resistive inks differ from conductive inks in its conductivity. Resistive inks are normally specified by their resistivity, which is measured in ohms per square. While conductive inks might have a resistivity of milliohms per square, resistive inks range as high as megohms per square. The silver additive in conductive inks is usually replaced with carbon found in conductive inks. Most resistive inks are epoxy based although many manufactures are developing polymer formulations which are designed specifically for applications involving flexible polyimide film substrates. These products are much more sophisticated formulations than the carbon mixed with a two part epoxy that physicists have used in the past. The range of resistivity available is larger, usually 100 ohm per square to 1 megohm per square. The repeatability of the resistance values is much better, usually better than +/- 25 percent, and most important, these products have been designed for automated silk screening equipment. Curing can be done in either a box oven or an IR belt furnace, although if were smart, we will formulate the ink to have the final cure on our molds. Resistance values between 10 kilo-ohm per square and 50 kilo-ohm per square are required. Figures 11 and 12 show the silk screened resistive elements on the prototype signal electrode used in our AGS tests.

4.4. Radiation Damage

4.4.1. At this time very little is known about the neutron flux within the GEM detector. Brookhaven National Laboratory, has just completed a series of radiation damage tests at the AGS on polyimide materials and laminates. These tests are being performed for the SSC magnet group. It is expected that the polyimide materials being tested at BNL will receive much higher neutron dosage's then those expected within the GEM detector. All of the materials that we are investigating for possible use in our signal electrodes are included in these tests. Our selection of materials will be based on the results of these tests.

4.5. Production Scenarios

4.5.1. We have gained a great deal of experience over the years with the production of oversize printed circuit boards. We have learned many lessons. The first is quite obvious. Their are no simple solutions to complex problems. Second, money and outside experts cannot solve all problems. And finally, that the job must be matched to the manufactures equipment and capabilities. Modifying standard production methods or using production equipment in a method in which it was not intended to be used, usually results in an inferior product and *always* results in increased costs and delays. We intend to solicit bids from manufactures that have proven experience in the manufacture of large flexible circuits and have the appropriate equipment. The manufacture will deliver a completed signal electrode ready for bending into the accordion shape and requiring only post curing of the adhesives and inks. Electrical connections, e.g. signal and high voltage connectors, are installed after the electrodes are bent and thermo molded into there required shape.

5. Bending Signal Electrodes

5.1. The bending machine is designed around the thickness specifications and load requirements for the absorber electrodes. The signal electrodes are much thinner. To compensate for the differences in thickness, sheet aluminum is placed on each side of the kapton signal electrode to make up the difference. This filler material is bent along with the signal electrode. To duplicate the angles correctly, the kapton sheet must be placed in the mid plane of this package.

6. Pressing Signal Electrodes

6.1. In general most polyimide materials do not have a good memory. Over time a bent piece will tend to flatten out. Handling accelerates this process. The shape of a bent kapton electrode is held primarily by the copper cladding. This is usually sufficient in areas where there is ample copper. Over bending can help to compensate for springback. The problem areas are at the extreme ends, the area where the connections and high voltage bus exists. The amount of copper is usually considerably reduced in these areas to allow space for connections and to provide high voltage isolation. A four meter signal electrode that does not have the proper shape is a difficult item indeed with which to build a stack. Retaining the original shape of the electrode is paramount. We are exploring two methods to insure that we will be able to retain the required shape.

6.2. The first is an approach that was developed for our absorber plates. We will manufacture the signal electrodes using "B stage" adhesives, i.e. adhesives that have not been fully cured. The adhesive flows slightly while being cured in the mold allowing the two parallel surfaces to relieve the stresses built in during the bending process. As the adhesive cures and sets the shape of the mold is retained.

6.3. A second approach is to thermal set the polyimide electrode in the mold. Materials differ in the time and temperature required to thermoset. In general, the time is long and the temperature is high. This is not the preferred method.

7. Tests

7.1. Two types of tests are required. Electrical and mechanical. The mechanical test is primarily a cryogenics test. The kapton signal electrodes are thermo cycled to cryogenic temperatures. A visual inspection for delamination and cracks follows along with a continuity test for all resistive elements. High Voltage tests complete the procedure.

8. High Voltage

8.1. There are two general areas where high voltage breakdown can occur. The first is on the signal electrode e.g. from high voltage strips to the inner signal strips, or from the high voltage electrode to a ground plane or a low voltage connection. The second general area is across the krypton / argon gap.

8.2. To be able to separate the two sources of electrical discharge we follow a simple design rule. Any span on the readout board between high voltage electrode and ground must be at least 50% larger than the argon gap. This requirement allows us to test the individual high voltage strips at 150% of the maximum gap operating voltage. When the stack is assembled, any discharge must occur across the krypton / argon gap.

8.3. Leakage currents at ambient test conditions is determined primarily by the humidity in the air. To minimize this contribution, and to provide increased sensitivity to surface contaminates, we require a controlled environment where the relative humidity is maintained at a constant 40% level. Leakage currents in excess of 50 to 100 nanoamps per gap indicate a potential problem area.

9. Signal Connections

9.1. The integrity of the signal connections can be determined in several ways. When there are no active elements between the signal source and output connector, a capacitance scan is a simple and proven method. A computer controlled scanning device measures the capacitance of each connection and displays this information graphically. The failure to make a connection to a capacitive source such as a signal electrode will show up immediately.

9.2. If active elements are situated between the signal source and the output connectors this method cannot be used. Instead we design the signal electrode printed circuit board to provide a small capacitive overlap between the high voltage bus and the signal electrodes. This coupling capacitance must be small compared to the inter-electrode capacitance. The high voltage electrode is pulsed and the coupled signals are measured on each signal electrode. Failure to make an adequate signal connection will show up immediately.

9.3. Another continuity test that we have often used is to measure the input noise of each channel. The detector capacitance raises this noise level and a change of input capacitance caused by a bad signal connection or bridging to an adjacent channels is easily recognizable.

10. Special Tools and Test Equipment

11. Endcap Calorimeter

11.1. The general division of the endcap calorimeter is similar to the barrel. We have an accordion EM section and fine and course hadronic sections.

11.2. The EM section of the endcap has an accordion projective structure with a flat front face. This is an attempt to preserve space. See figures 5 and 6

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12.2. Figure 2: Conceptual drawing of the accordion structure.

12.3. Figure 3: Artists view of prototype structure.

12.4. Figure 4: Assembled module showing cable routing.

12.5. Figure 5: Conceptual drawing of endcap EM accordion structure.

12.6. Figure 6: Endcap accordion module without support structure.

12.7. Figure 7: EM accordion segmentation.

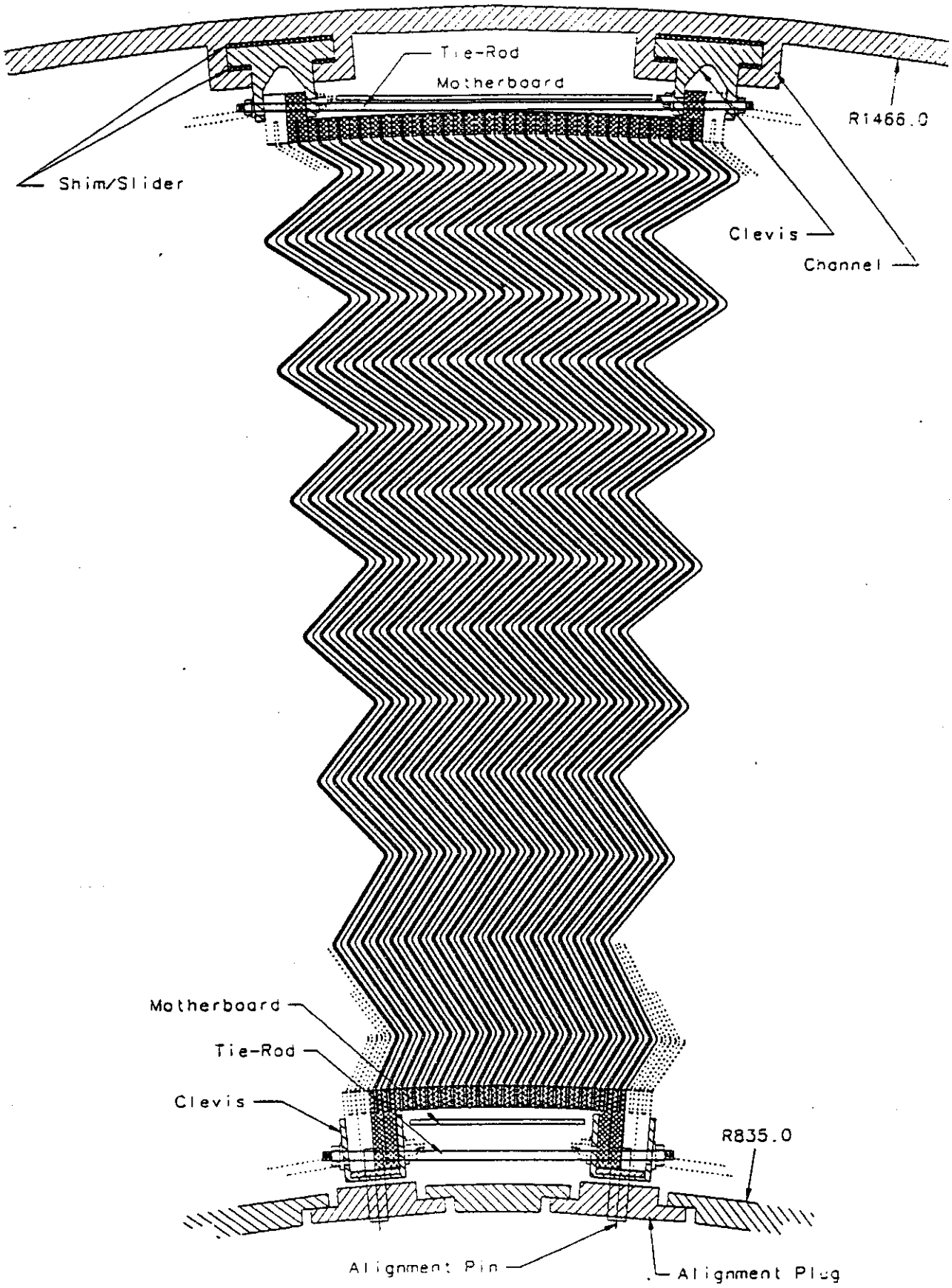
12.8. Figure 8: Conceptual drawing of assembled EM electrodes.

12.9. Figure 9: Conceptual drawing of signal electrode segmentation.

12.10. Figure 10: Barrel signal electrode before and after bending.

12.11. Figure 11: Illustration of silk screened resistors.

12.12. Figure 12: Expanded view of silk screened resistors.



Typical Module Lay-up in Section

Figure 1

Accordion Structure

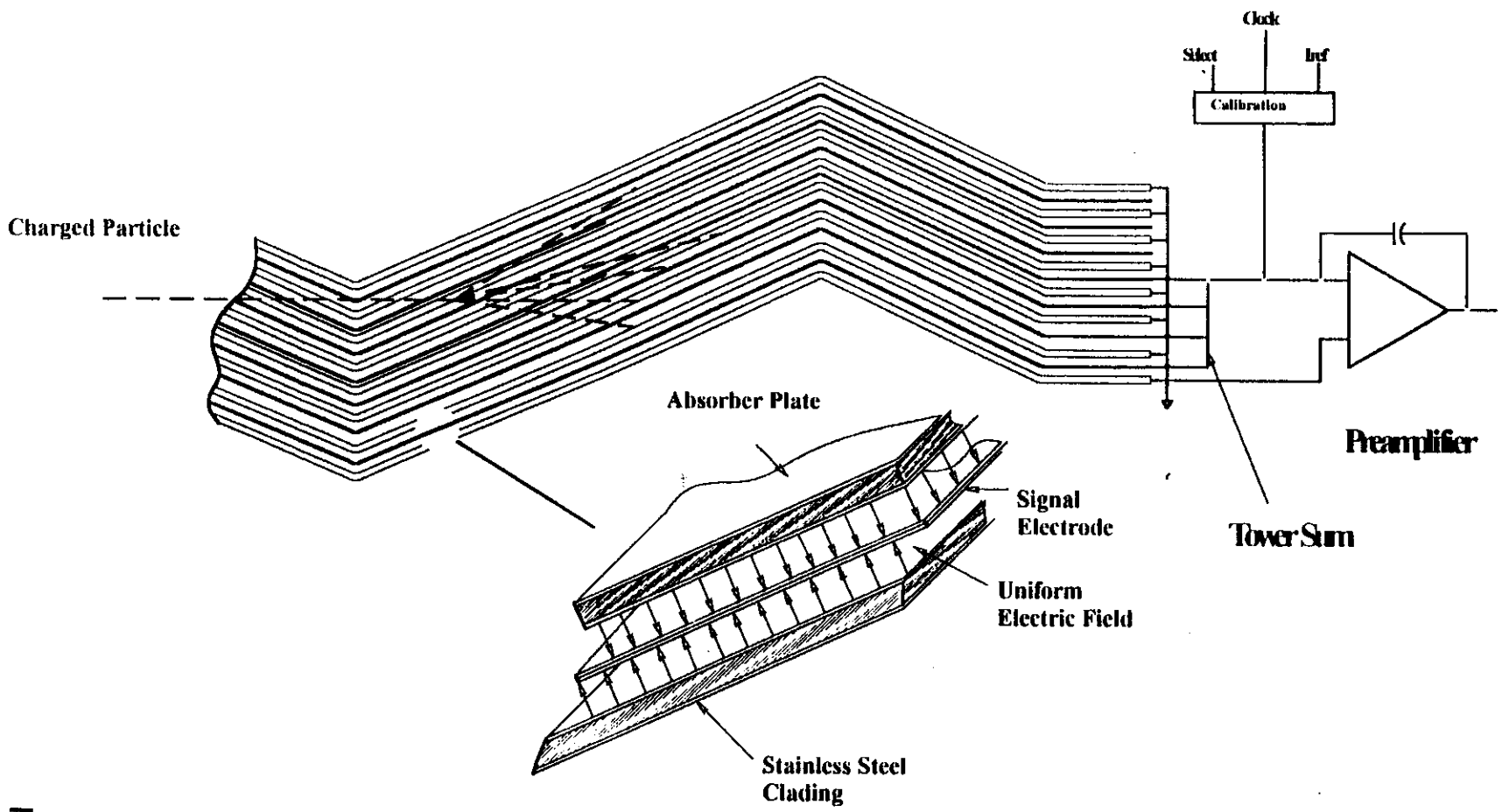
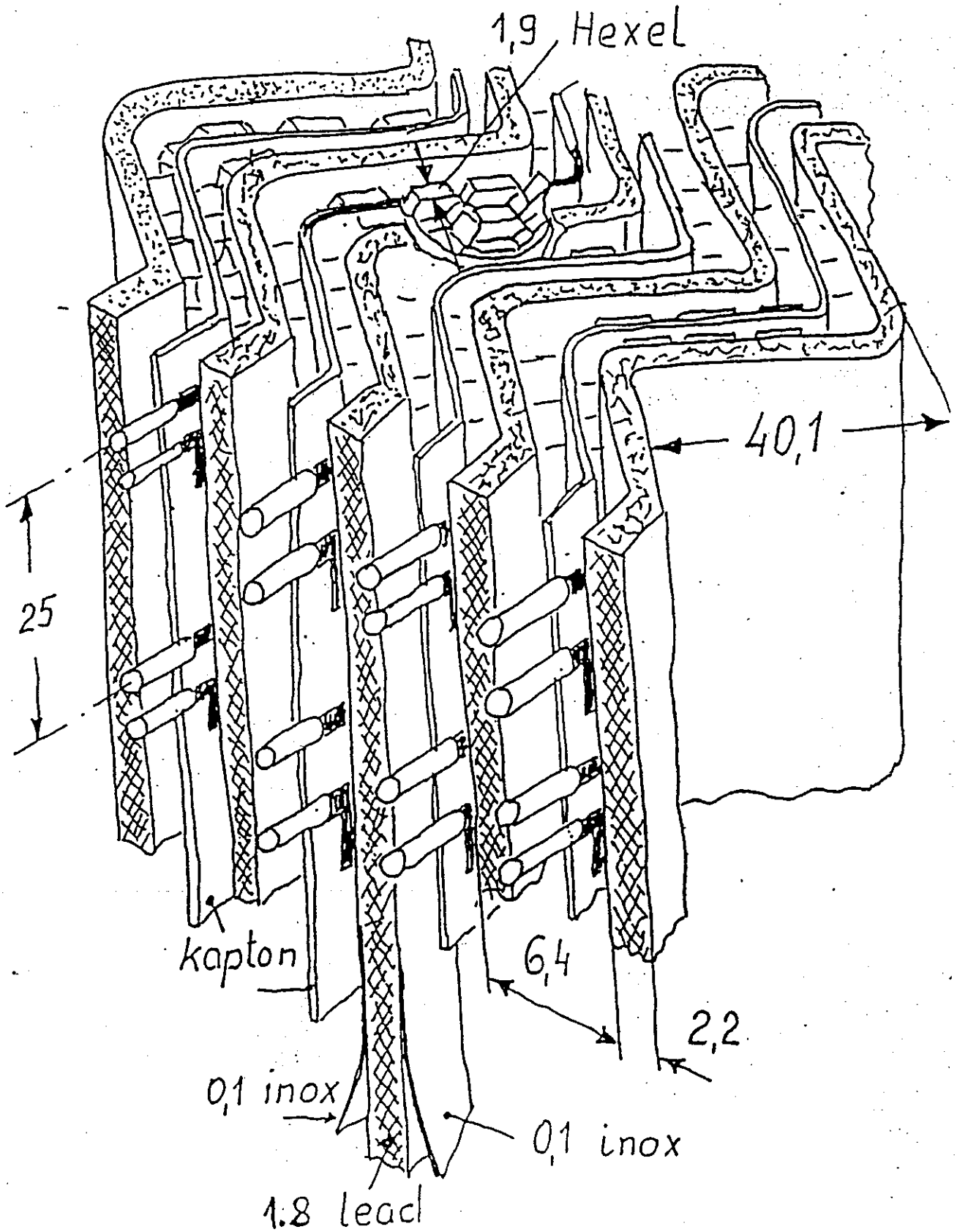


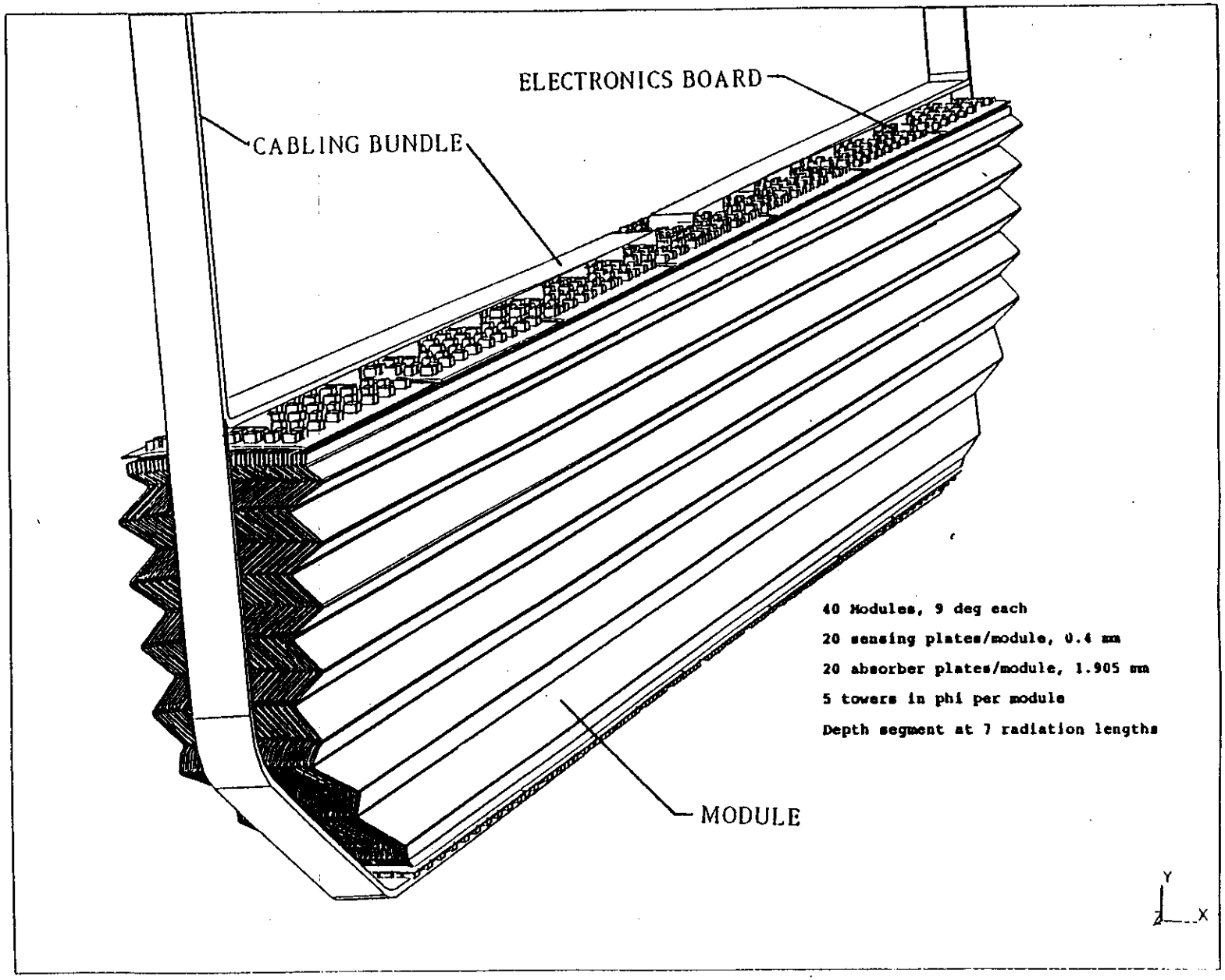
Figure 2

DSM



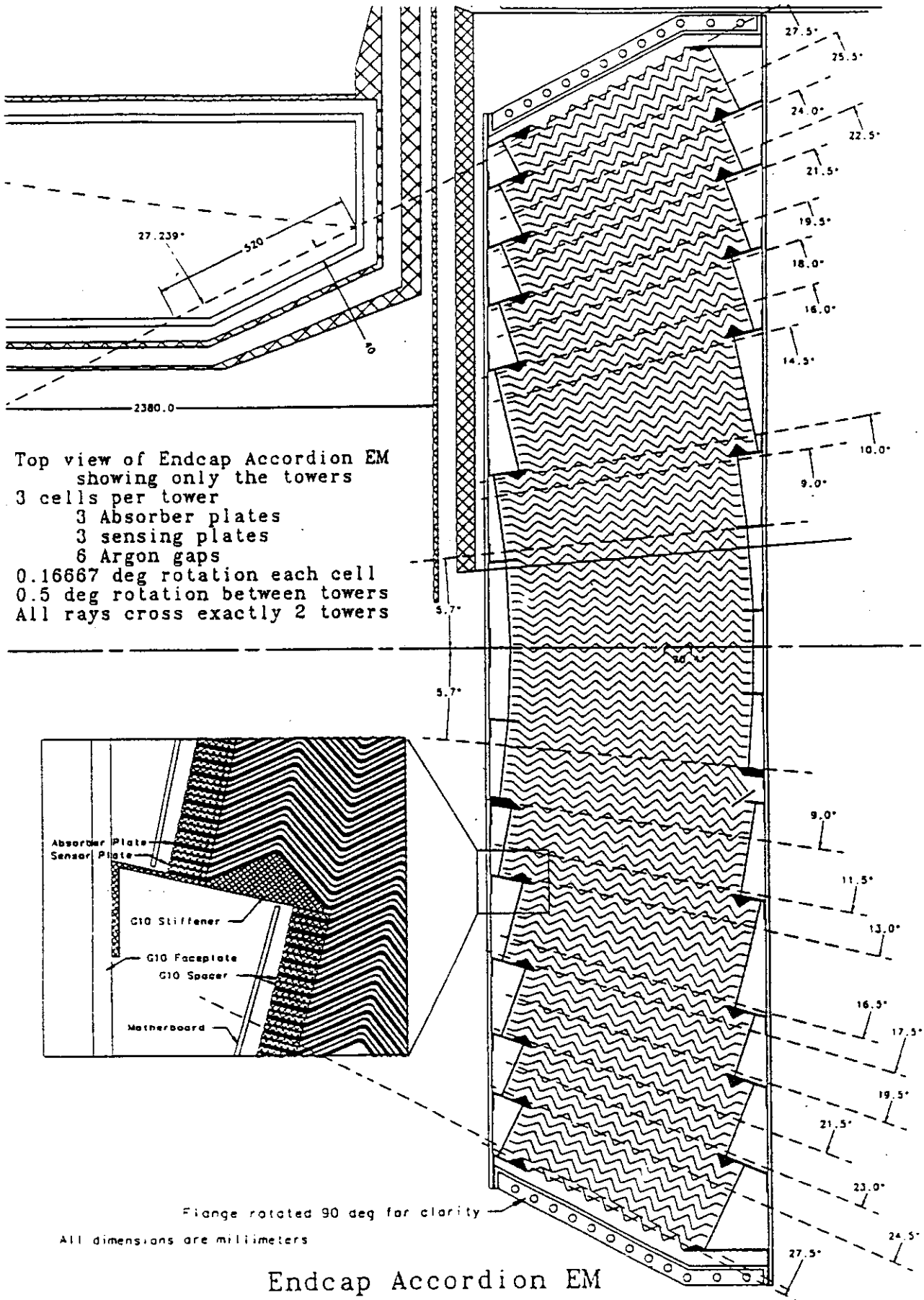
"Artists view of prototype structure.

Figure 3



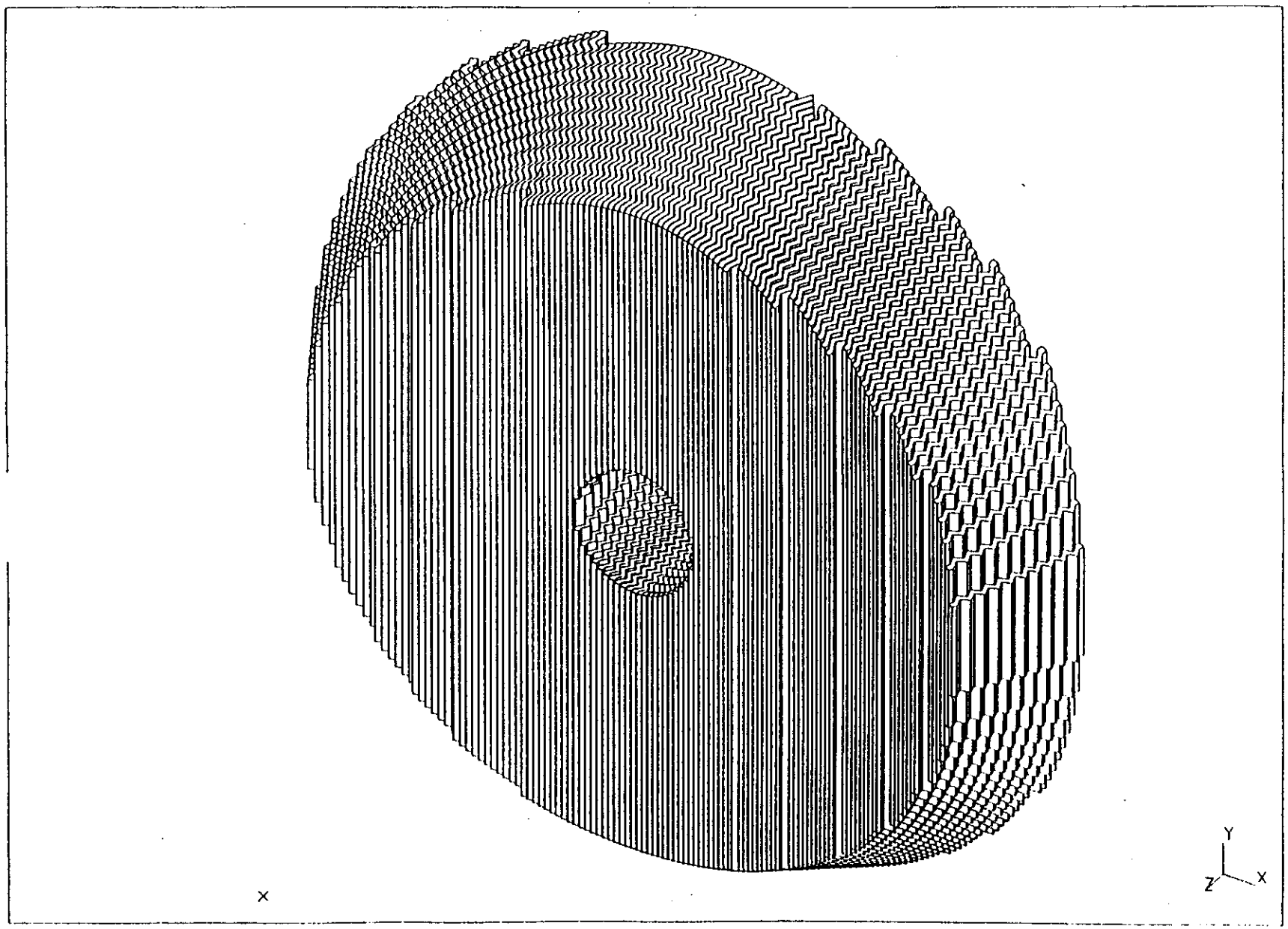
Assembled Module Showing Cabling Bundles

Figure 4



Endcap Accordion EM

Figure 5



Endcap Accordion EM Without Support System

Figure 6

EM Accordion Segmentation

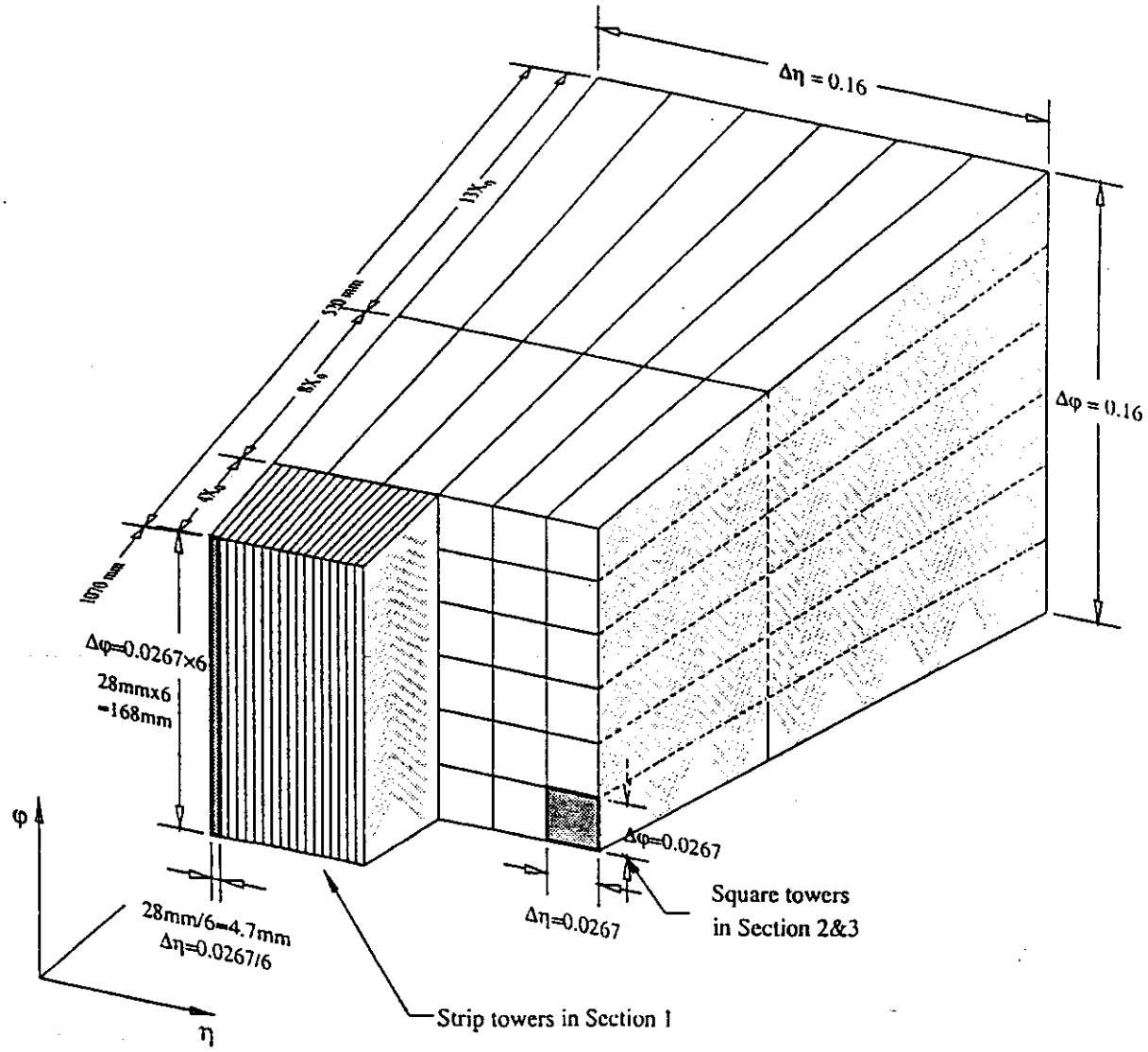


Figure 7

EM Accordion Electrodes
1st Section ($4X_0$), $\delta\eta$ Strips

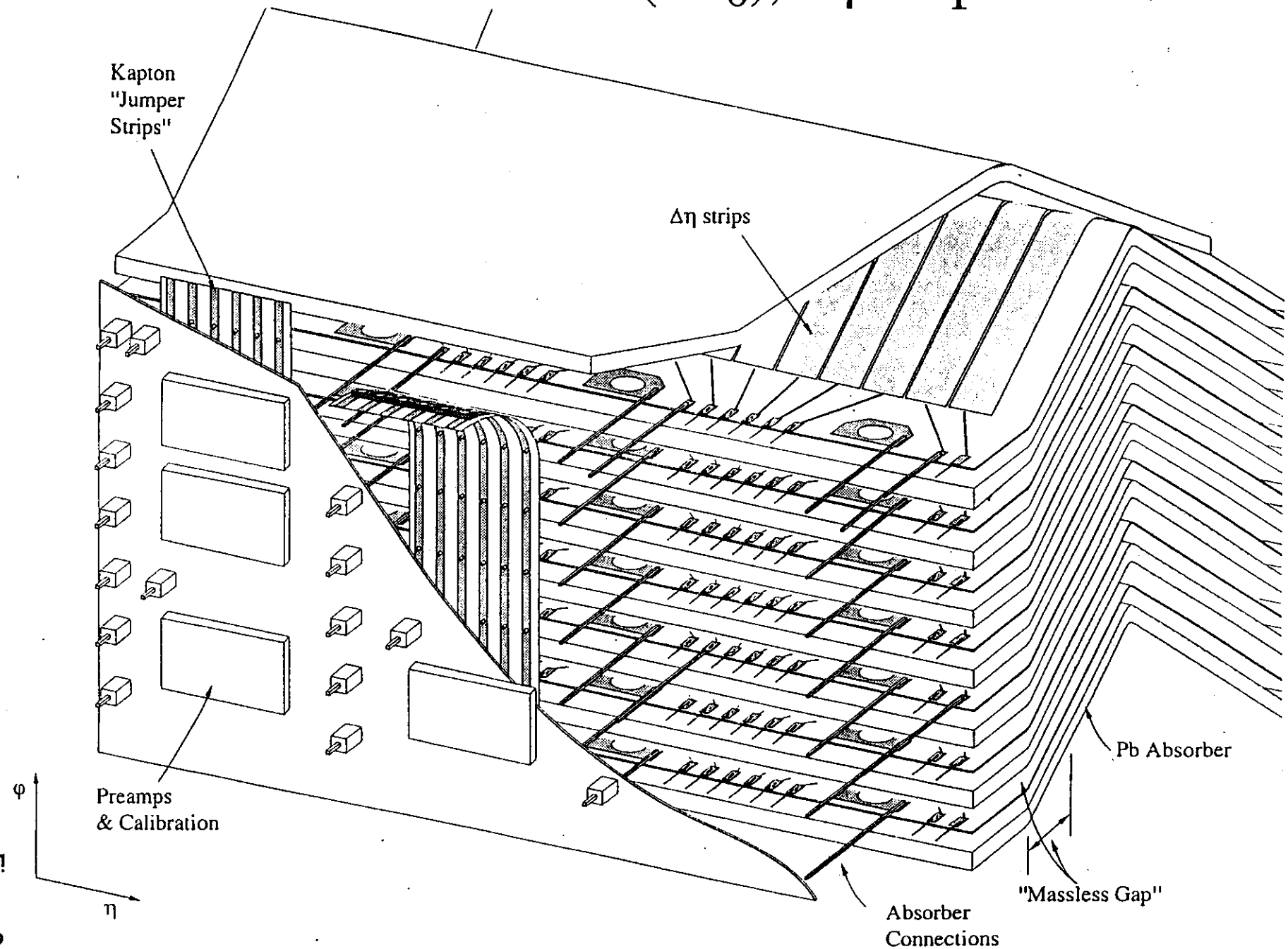


Figure 8

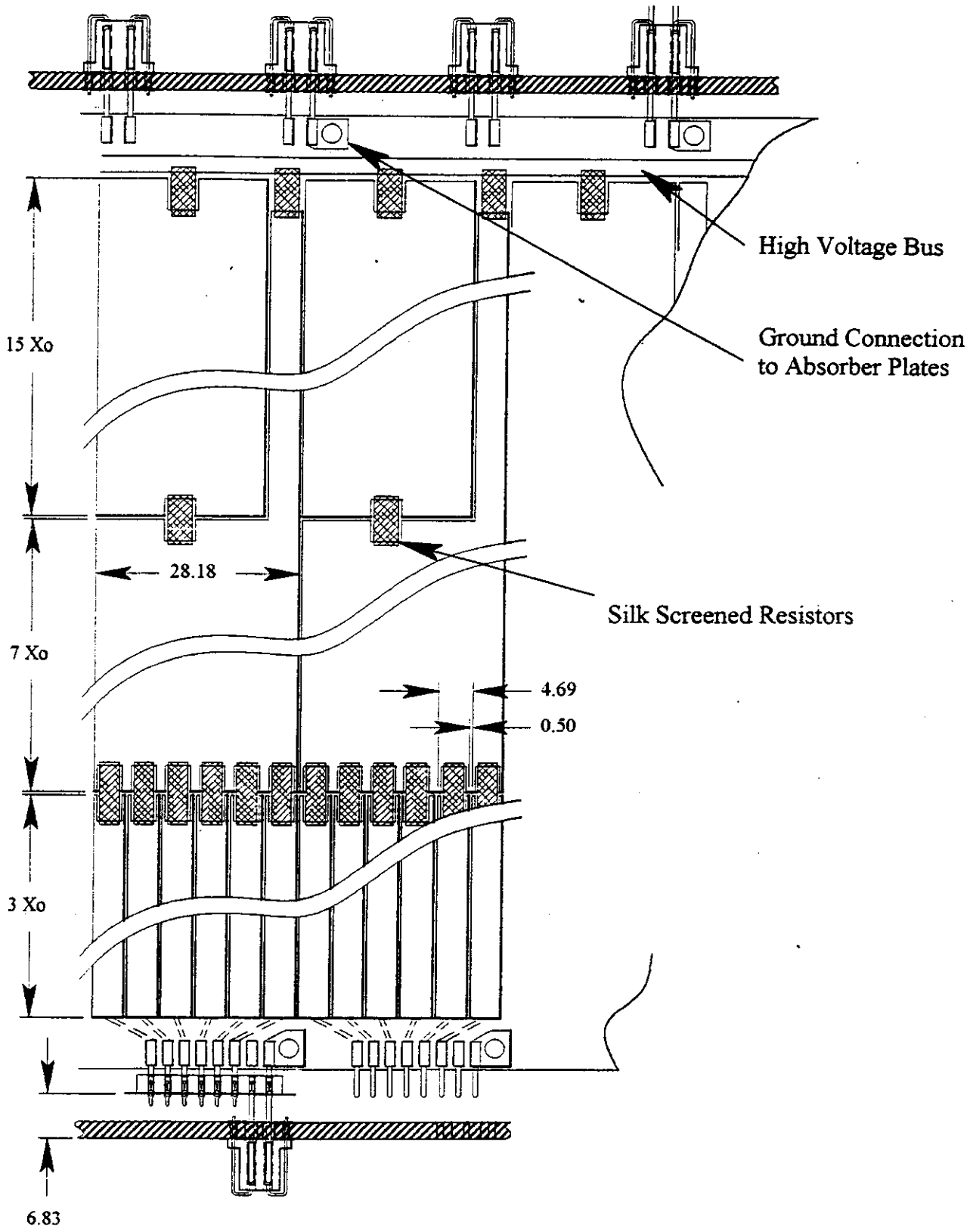
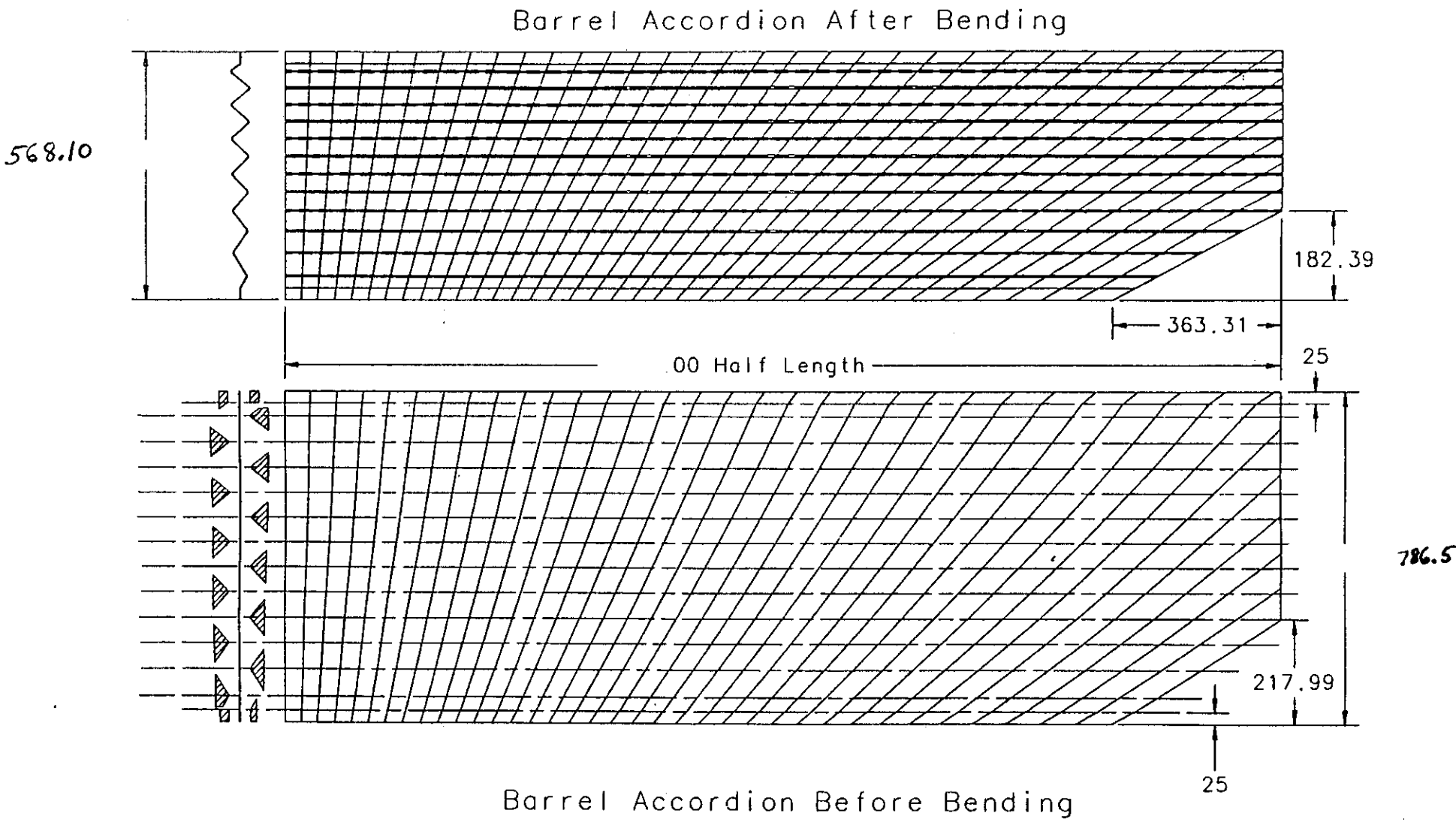
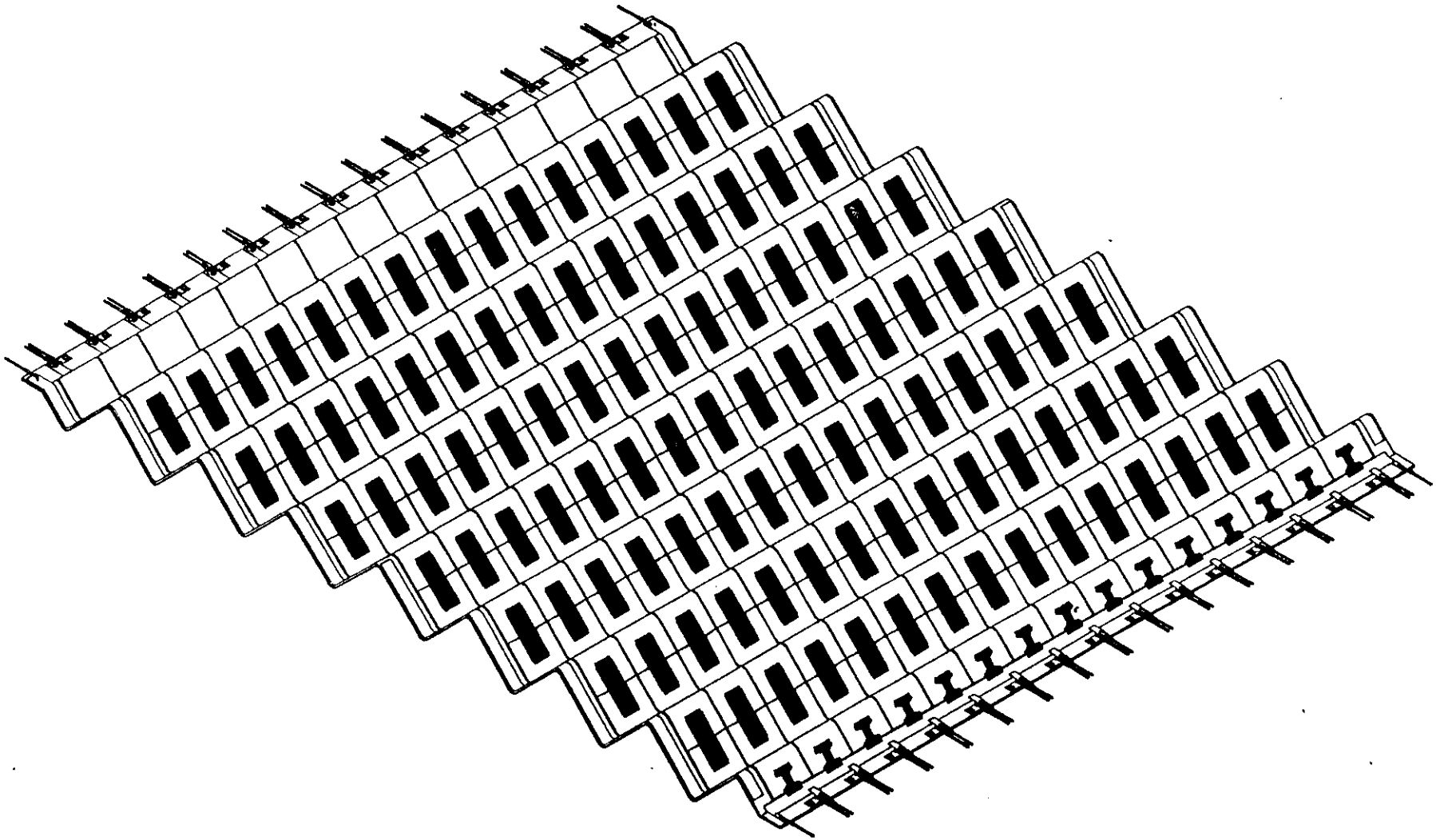

High Voltage Bus
Ground Connection
to Absorber Plates
15 Xo
28.18
Silk Screened Resistors
7 Xo
4.69
0.50
3 Xo
6.83

Figure 9



Typical but obsolete
200 absorber and 200 sensing plates
with .04 X .04 Segmentation

Figure 10



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0-20' 20'-60' OVER 60' FRACTIONAL TOLERANCE			FINISH				
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Figure 11

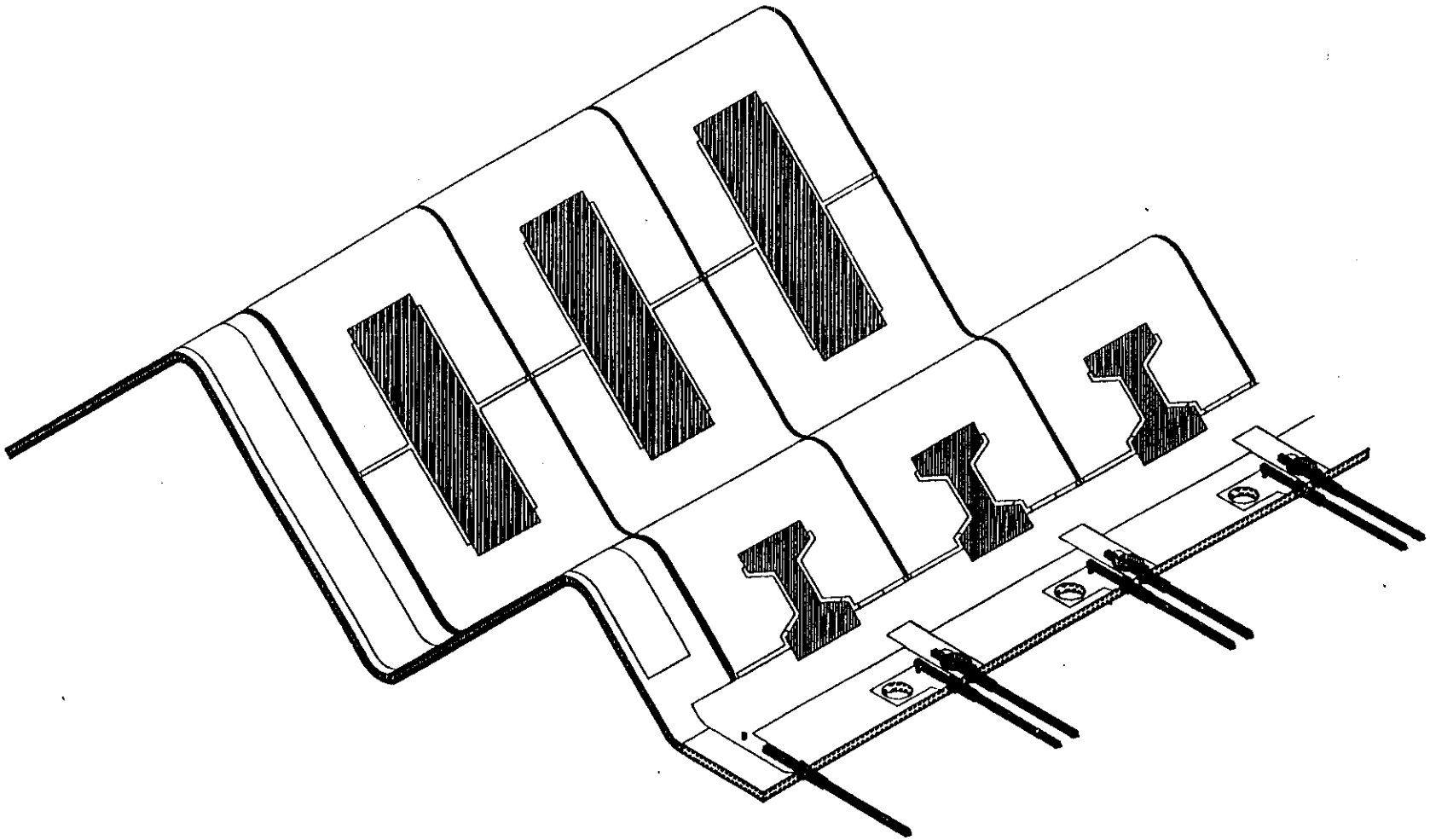

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Figure 12