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Scintillating Tiles
Production and Light Readout

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A report is given on discussions held at Fermilab and CEBAF on techniques and considerations in the production of scintillator tiles with WLS fiber readout. Emphasized are material selection, groove cutting, gluing, fiber splicing, mirroring, optical coupling, and tooling.

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Introduction.

The latest specifications for the Scintillating Barrel Calorimeter of the GEM detector [1] (Fig. 1) call for the construction of 44 modules about 60 cm thick, 100 cm wide, and 500 cm long. These will have 8 layers of absorber plates interleaved with four layers of scintillator tiles (Fig. 2). Scintillating layers are made of several mm thick tiles forming projective towers of the size $\Delta\eta \times \Delta\phi = 0.16 \times 0.16$ matching the 2 x 2 hadronic towers in the liquid hadron calorimeter. The size of the tiles is approximately 50 cm x 50 cm at 90 degrees and 50 cm x 87 cm ($\phi \times \theta$) at the end of the barrel. Each tile is read out by a few straight WLS fibers embedded in the tiles parallel to the z-axis and arranged uniformly over the tile area (Fig. 3). Even though tentative decisions have been made regarding such important questions as to fiber kind, size and numbers, tile kind and thickness, placement of fibers in tiles, splicing, glueing, readout, etc., it is extremely important for the GEM collaboration to look critically at the experience gained by other collaborations. Extensive research has been done at Fermilab for the SDC and CDF plug upgrade calorimeters that employ tiles. Similarly, CEBAF has done much tile related research for the CLAS detector. We visited Fermilab and CEBAF for informal discussions with some of the physicists and technicians who have done this work. Following is our report on pertinent information to the GEM project. An additional aim was to get acquainted with some of these people so that a dialog can be established with them regarding problems we may encounter. We are extremely grateful to them for taking time to discuss with us manufacturing techniques and many other aspects in great candor.

1. Light collection from scintillating tiles.

The most natural way to collect light from thin tile of large area is to embed WLS fibers in the scintillator. A number of groups working with this technique have shown that high uniformity up to 1-2% can be achieved for different tile sizes and shapes [2,3]. Placement of readout WLS fibers on a side of the tile increases the non-uniformity, for instanse, up to 6% for a 10 cm wide 1 cm thick strip [2] and worse for wider and/or thinner tiles. Readout with the help of light guide or clear fibers give rise to longitudinal non-uniformity and depends largely on light attenuation in the scintillator itself.

The CEBAF group [2] has shown that using embedded fibers helps to increase the longitudinal light attenuation length in long scintillator strips up to values of 5-6 m from 2-3 m, and hence reduce the non-uniformity of response.

This technique allows to collect light from scintillators and transport it long distances. For instanse, the response of 4-6 mm tile with SDC designed readout using one unglued fiber embedded close to the edge and circling the tile, is about 2 p.e./MIP [3]. The response of 1 x 10 x 100 cc tile with 5 WLS glued fibers 2.5 m long is as high as 12 p.e./MIP [2].

2. Scintillator.

2.1 Scintillator type.

The two principle scintillator vendors are at present Bicron and Kuraray. Fermilab groups conclude that Kuraray scintillators are superior to Bicron's. This is based on quality variations and cost especially for the less than 1cm thick sheets. They stated that quality control by Bicron is poor while for Kuraray products it is very good. Bicron's cost depends on cell sizes determined in the manufacturing process. Thus thin sheets can cost more than the thicker ones, because smaller cells must be used. Kuraray's cost is more or less proportional to the amount of scintillator supplied. It was pointed out that setup is a cost factor and one needs to find out where next price break comes in. In Japan industry produces the tiles and KEK does the R&D in close cooperation with industry. SDC uses Kuraray SCSN-38 6mm thick (polystyrene) for the hadron section and SCSN-38D 4mm thick (PVT) for EM. PVT has higher light yield, but polystyrene is easier to machine due to higher melting temperature.

Bicron BC408 has comparable light output to SCSN-38D, while BC404 has a 20% higher light yield with K27 WLS readout due to better matching to absorption spectrum [2,3].

It was pointed out that in order to test quality of a manufacturers product it is essential to receive a whole sheet of scintillator. Small samples are often cut from the middle or from the most uniform region as determined by the manufacturer and do not represent the true quality of the product.

2.2 Scintillator cutting and grooving

At FNAL machining is done with carbide tipped milling tools. The plastic sheets are vacuum clamped on to a THERMWOOD table 5x12 feet (cost $180K plus accessories = $250K). Cutting is done with tool speed of 15K to 30K RPM and feed speed of 90 inches/min for 1mm groove. Cutting is done with several passes of 1/2mm depth at a time. Ball grooves are done as single last pass and may be symmetrical or extend to one side of the groove only. All operations are under computer control in 3 dimensions. Accuracy is 100 micron in x,y and 25 micron in z (up-down). They also make multi-tile structures by cutting grooves to 1/4 mm from bottom and fill the grooves with epoxy colored with TiO_2 for light isolation. This results in less than 5% cross talk. Additional decrease in cross talk can be achieved by painting the surface near the separation grooves with Magic Marker. To produce individual tiles the cut is made all the way through. Speed of tool rotation and feed are determined empirically for each material. In general the wider the groove and the deeper the tool position, the faster the tool RPM and feed. The cutting area is blown clear of chips with 4 air jets and cooling is done with chilled dry air [4].

For straight grooves CEBAF group uses circular cutters made of micro-grain carbide obtained from Action Tool Services, Inc. [5] that are specially ground for the desired groove shape. The cost of a blade is about $200. Rotation speed is 3000 RPM (upper limit for this type of tool) with feed speed of 4 inches/min for 2mm groove with one pass. For multi-parallel grooves the cutters can be ganged. Cooling is done with 50/50 mix of clean water and mild dish soap sprayed through air mist. The appearance of the cut surface looked quite smooth and transparent. Note that the tool speed at the cutting surface is a factor of five or more higher for the CEBAF cutter than the mill used at Fermilab.

Fermilab produces mega-tiles which is an assembly of many tiles on one sheet and allows to simplify tile support and positioning. This large scintillator is then sandwiched between non-scintillator sheets and packaged in a thin aluminium can. The fibers are routed to an optical coupling plug in grooves in the sandwiching material. This arrangement is much more complicated than what we will require for the GEM outer barrel.

2.3 Tile production with grooves

Grooves can be machined or the tiles can be manufactured with grooves in place. Extrusion is feasible for straight parallel grooves, but it is unclear if the extruded tiles can be made with parallel surfaces. For 10 cm wide and 1 cm thick tiles the thickness variation can be as high as 10%. For thinner sheets this can get worse. The advantage of extrusion is that the optical quality of the groove is high and the obvious cost advantage.

Mold injection is another method for producing grooved tiles. Complicated shapes are possible. This method has been used for the shish-kebab calorimeter in BNL E-865. So far it has not been shown that large size tiles can be produced in this manner and whether the sheets will be flat enough. The advantage is low cost and that all machining can be eliminated.

For either of these methods extensive R&D work will be required.

2.4 Tile wrapping

Aluminium foil, aluminized mylar, teflon, Tyvek, and black plastic were compared [2] as wrappings for tiles with respect to light yield and uniformity. No wrapping and black plastic were identical. Tyvek, manufactured by DuPont, [6] is a white plastic (not cellular) product, usually 50 micron thick and used for envelopes by Federal Express, and teflon were found to be the best, yielding twice as much light as no wrapping. Tyvek does not scratch or adhere to the scintillator, is very tough, inexpensive, and extremely radiation hard [7]. No degradation was detected up to 5MR radiation dose. A few percent non-uniformity was seen in CEBAF tests for Tyvek, but with still about 20% higher light output than Al/mylar see (Fig. 4). Al/mylar degraded in radiation environment and teflon is known to be radiation soft.

3. Fibers.

3.1 Fiber material.

Fermilab personnel expressed their preference for Kuraray fibers to the Bicron's products. They claim that Bicron products exhibit variation in quality, light yield and variation in fiber diameter. They use Kuraray's Y-11 WLS fiber with K-27 dye developed by Alan Bross. The cost for the WLS and clear fiber is 50 cents/foot. Kuraray is secretive about the content of their products which makes it hard to evaluate observed differences in the product.

3.2 Fiber diameter

Fiber diameter is chosen as a reasonable compromise between light collection, splicing quality, and routing ease requirements. For example, for larger fiber diameter better quality splices and higher light output will be obtained, however, routing the fibers is more difficult. Fermilab (CDF plug upgrade and SDC) has considered 0.75mm, 0.83mm, and 1mm diameter fibers. The 0.75 mm diameter fiber has been ruled out because of splicing difficulties. Diameters 1mm and larger complicate routing problems, require larger PMT photocathode area, and require more space. 0.83mm fiber presents a good compromise. For the straight grooves and plenty of space the CEBAF group proposed 2 mm fibers for the CLAS detector.

3.3 Fiber splicing.

Fiber splicing is done at Fermilab with a splicer developed at MSU. This splicer holds the two fiber ends in a vacuum held vice, the fiber is pushed together with preset pressure in a quartz split tubing and fused with the heat from a projector bulb. A pre-shrunk transparent Peek hard tube [8] about 1 cm long is shrunk onto the splice to support the fused joint. Prior to making the joint the shrink tube must be prepared and the fiber ends must be cut. This is done with a razor with the fiber held tight in a brass block. Afterwards the joint must be tested for light transmission. Typically 90%-92% light is transmitted. When Kuraray switched manufacturing to produce a softer fiber (S-type, more flexible) the transmission dropped to 83%-85% for unknown reason. MSU is willing to manufacture a splicer for approximately 25K$. Quoted splice rate, including preparation and testing, is about 160 splices per shift for two machines and four technicians.

A much simpler splicer, consisting of a quartz tube with a heating loop works quite well [9]. The main disadvantage is lack of controlled pressure on the fiber joint, and that alignment is done only by the quartz tubing. Also, the fiber must be slipped out of the tube.

Care must be taken in cutting the fiber end in preparation for splicing. For instance, cutting bare unclamped fiber can damage the cladding and/or core resulting in a poor joint. Cutting fiber with a heater device causes melting of core with cladding and although the surface looks fine yields a poor joint. Cutting the fiber on a bias also is a bad idea due to possible displacement during splicing.

3.4 Fiber mirroring

The light output and uniformity of light collection are increased if the fiber end is mirrored. Aluminizing can be done by evaporation or sputtering. The former is easier, but the latter yields a harder and more resistant surface. Evaporated aluminum is easily rubbed off the surface. It was suggested that a thin acrylic coating, applied by dipping, will help the adhesion of the aluminum. Also, evaporating silicon monoxide is supposed to protect the mirror. It is necessary to polish the surface and clean the ends with ethyl alcohol before evaporation [10]. CEBAF uses 1 micron diamond paste for polishing [11], whereas Fermilab takes a thin cut with a diamond cutter instead. The fiber ends should be cut at 90 degrees to the fiber axis with high degree of accuracy.

3.5 Fiber glueing

Fermilab has decided not to glue in the fibers. Since the fiber path is in the shape of a loop close to the edge of each tile (lower case sigma shape), the fiber is held in place by spring action either in a ball cut groove or straight groove into which the fiber is threaded after tile structure has been assembled. They found that glueing the fiber increases the light yield by 30% in the 4mm or 6mm tiles. Note that this is in sharp contrast to other reports, see later. Bicron 600 glue was tested with a Co-60 source and turned black in a field greater than 1MR. Epotek 302 tested good and is also chemically safe. The longitudinal non-uniformity inside one tower for SDC with 0.83mm fibers not glued has an RMS of 2% and tite to tile variation is about 6-7%. The uniformity is worse when the fibers are glued. To remove air bubbles the glue is spun. Variation was found in light yield for variation in viscosity. Light yield was less for the lower viscosity. The reason is not clear, however, stress accelerated chemical reaction or physical factors could be the cause. When glue is used the fiber should be gently placed into the glue filled groove starting at one side and working ones way toward the other end. Advantages of not using glue include being able to repair breaks in fibers by removing and splicing and repairing damage due to creases.

In contrast to the Fermilab's findings, CEBAF data shows that the difference in light yield between glued fibers and unglued is a factor of two. Note that CEBAF used 2mm fibers BCF91A and BC408 scintillator. Fermilab's results were for 0.83mm fibers and scintillators from Kuraray. Also the quality of grooving could be sensitive to the effect of the glueing. The grooved surface appeared to the naked eye more transparent for the CEBAF finished cuts as compared to those produced at Fermilab. CEBAF and Univ of Virginia have tested a low viscosity, low exotherm, slow setting epoxy from Master Bond [12]. This epoxy has been tested to be radiation hard up to 1 Grad and it does not intrude into the cladding. The testing of a number of different glues is presented in ref. [13].

4. Optical coupling.

Two important issues in coupling the fibers to the phototube are the shape of the optical coupler and the contact between surfaces. The ideal shape for the mixer is a polygon with least sides. CDF is going to used a square mixer/coupler because of lower cost. One should avoid a cylindrical shape. Air gaps in the optical coupling are perfectly alright because the light emerging from the fiber subtends a narrow cone and there is no back reflection from the light mixer. To couple light mixer to PM different techniques are used. One is to glue them, another one is to use silicon cookie between them and mold the whole assembly in epoxy. Glueing seems to be simpler, the use of cookie probably gives more reliable long term stability.

5. Caveats.

This report is based on discussions with many people and represents our understanding of what we heard. We may at times have misunderstood what was said or meant and all discussions were informal and statements made from memory. However, we tried to critically evaluate the information we received. In order not to blame anybody for our distortions, we are not giving credit here to those kind people who shared their information with us.

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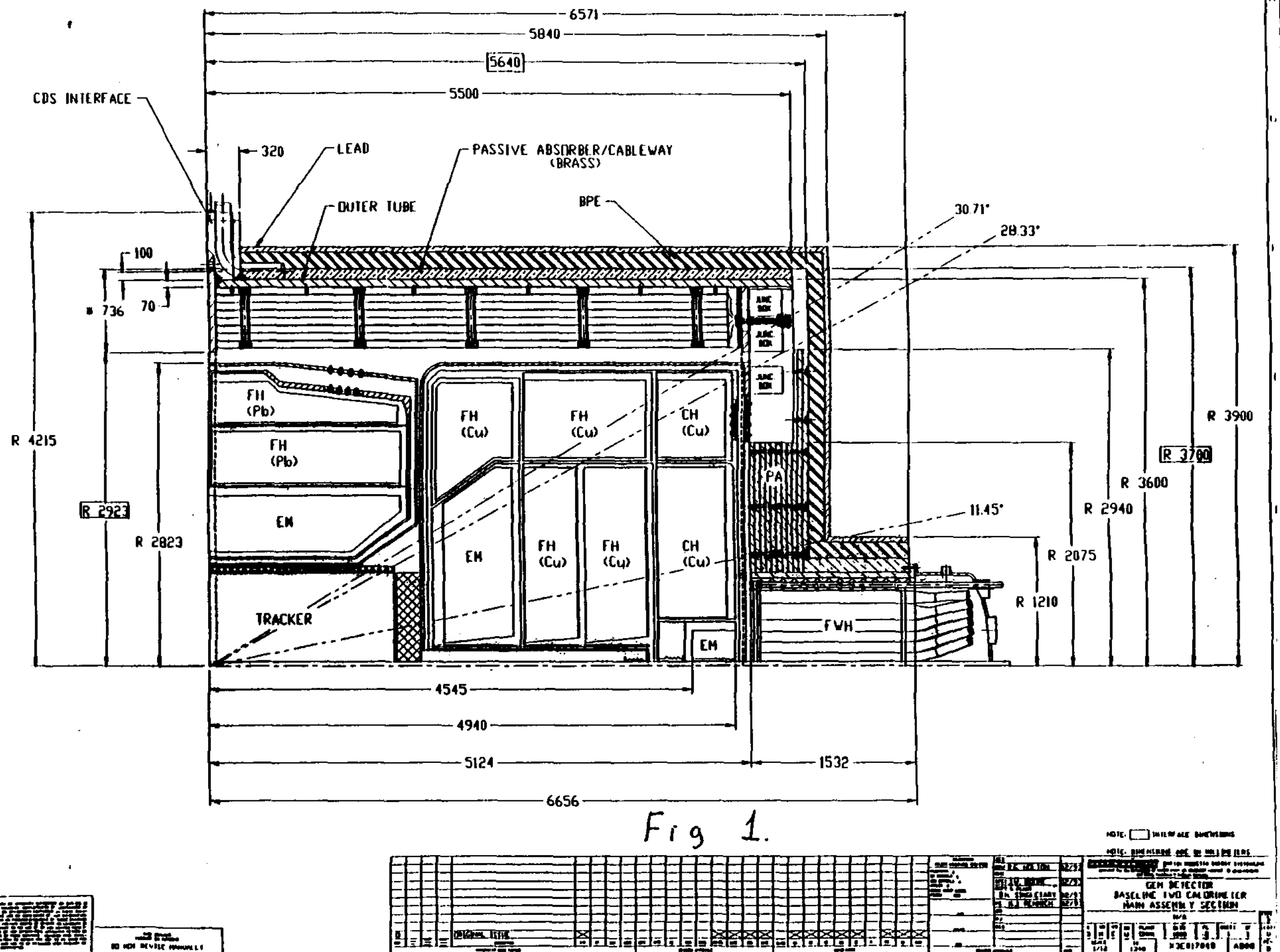
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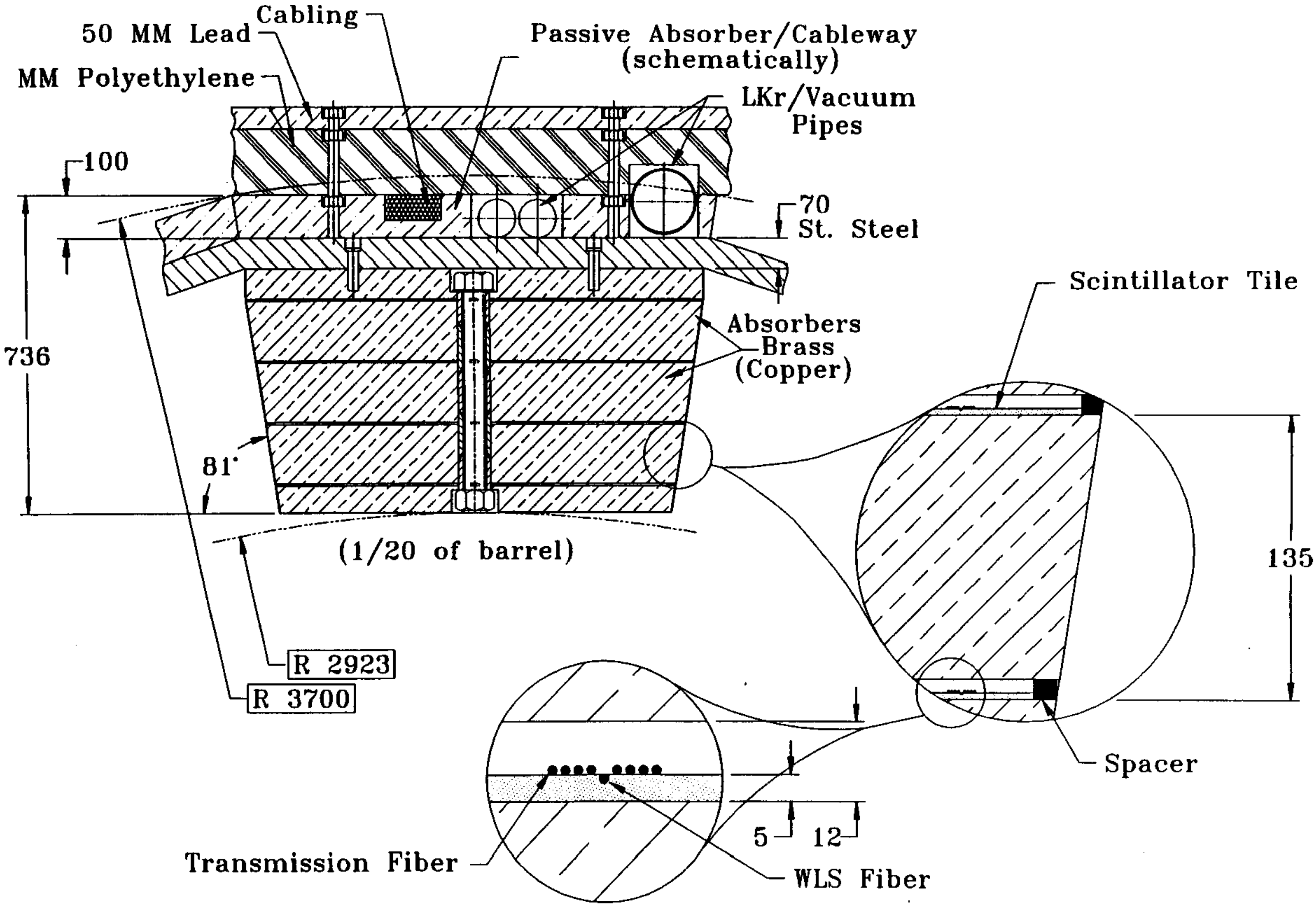
5840
5640
5500
CDS INTERFACE
320
LEAD
PASSIVE ABSORBER/CABLEWAY (BRASS)
OUTER TUBE
BPE
30.71°
28.33°
100
70
* 736
R 4215
R 2923
R 2823
FH (Pb)
FH (Pb)
EM
TRACKER
FH (Cu)
FH (Cu)
CH (Cu)
EM
FH (Cu)
FH (Cu)
CH (Cu)
EM
PA
FWH
11.45°
R 3900
R 3700
R 3600
R 2940
R 2075
R 1210
4545
4940
5124
1532
6656
GEM DETECTOR
BASELINE TWO CALORIMETER
MAIN ASSEMBLY SECTION

Fig 1.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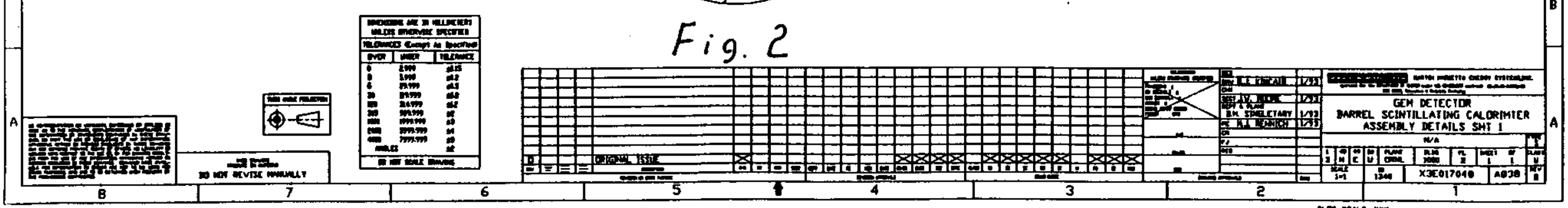
150 MM Polyethylene
Passive Absorber/Cableway
(schematically)
LKr/Vacuum
Pipes
100
70
St. Steel
736
Scintillator Tile
Absorbers
Brass
(Copper)
81°
(1/20 of barrel)
135
R 2923
R 3700
Spacer
5
12
Transmission Fiber
WLS Fiber

Fig. 2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BARREL SCINTILLATING CALORIMTER
ASSEMBLY DETAILS SHT 1
X3E017040
A038
ORIGINAL ISSUE
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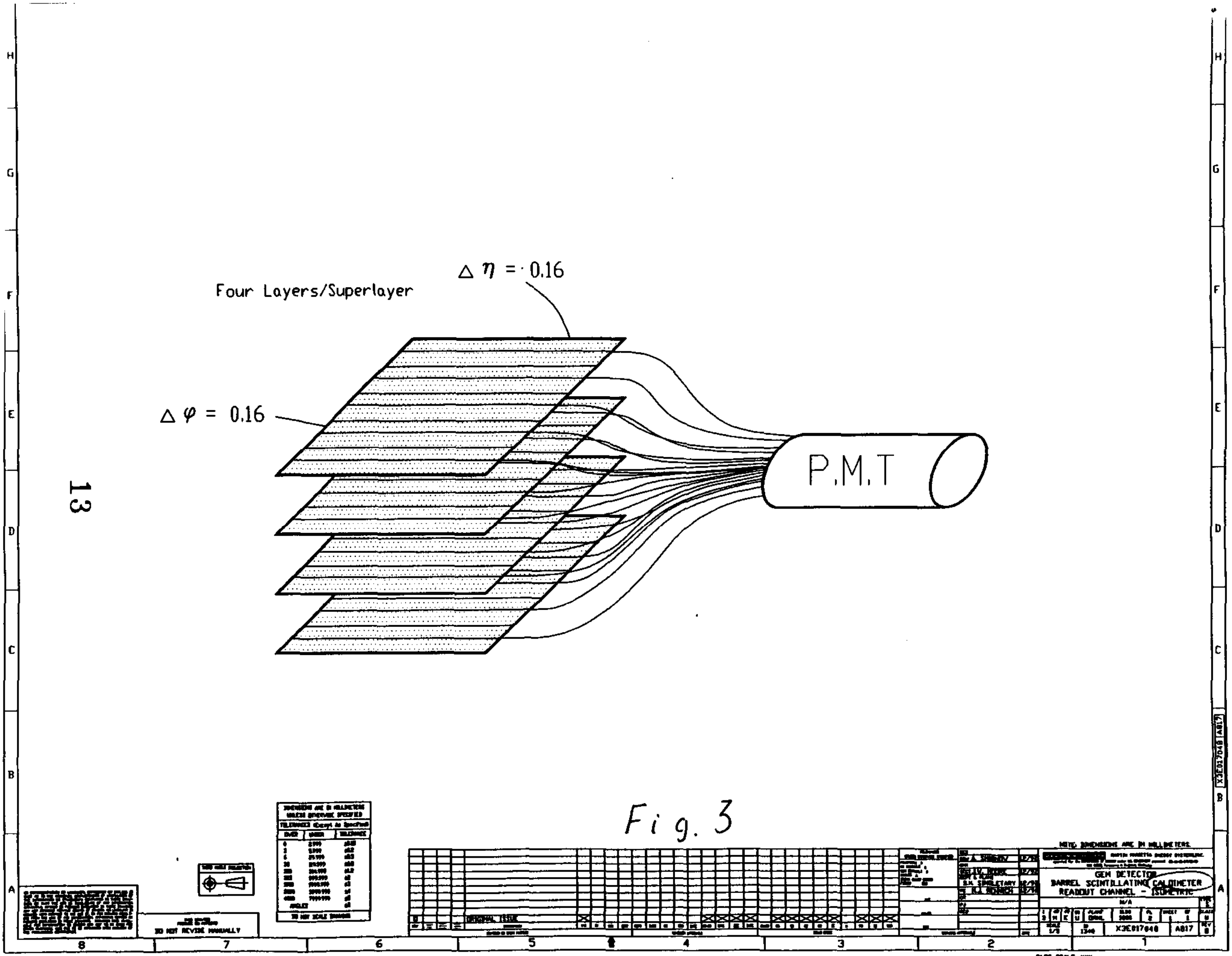
DO NOT SCALE DRAWING
PLOT SCALE: XXX


Four Layers/Superlayer
Δ η = 0.16
Δ φ = 0.16
P.M.T
GEM DETECTOR
BARREL SCINTILLATING CALORIMETER
READOUT CHANNEL - ISOMETRIC
ORIGINAL ISSUE
DO NOT REVISE MANUALLY
DO NOT SCALE DRAWING
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PLOT SCALE: XXX

Fig. 3

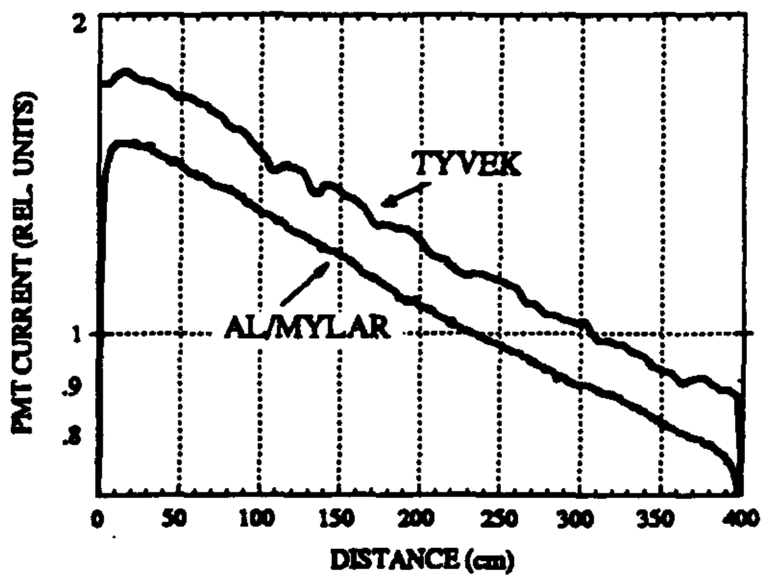

Fig 4: Uniformity of Tyvek vs Al/Mylar for BC408-BCF92 using Ru^{106}.