SCINTILLATING TILE/FIBER CALORIMETRY DEVELOPMENT AT FNAL

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The technique of calorimetry using scintillating tiles with waveshifting fibers imbedded in them for readout has been refined for use in SSC test calorimeters and for the CDF Endplug upgrade. The technique offers high light yield, good spatial uniformity, flexible readout mechanics and a very small "readout crack". Various production techniques have been developed and optimised, including control and correction of scintillator plate uniformity, techniques for splicing plastic fibers with low light losses, and laser-cutting of the groove in which the fiber is placed.

1 Introduction

The technique[1] of imbedding a waveshifting readout fiber into scintillator plate calorimetry has been developed and refined for use in both the CDF End Plug calorimeter upgrade[2] and for SSC calorimetry for the Solenoidal Detector Collaboration [3]. The basic method is illustrated in fig. 1. Scintillating plastic plates ("tiles") are prepared with wavelength-shifter (WLS) optical fibers imbedded in them for readout. Blue scintillation light is produced in the tile and is trapped by a combination of total internal reflection and specular reflection from an aluminized wrapping. Some fraction of it hits a green waveshifter fiber and is shifted. Typically 4% of the shifted light is captured by the fiber (in each direction), and can be transported to the outside of the calorimeter through the fiber. The path of the readout fiber can be either a simple "U" or a serpentine pattern for improved optical coupling. As they leave the plate, the waveshifter fibers are spliced onto transparent readout fibers. These fibers are bundled together with fibers from other plates, and each bundle is taken to a phototube to form the readout for a tower of calorimetry. This pre-assembled and tested tower of scintillators is then inserted into the absorber stack to form the completed module.

Arbitrary lateral and depth segmentation is possible with appropriate bundling of fibers. For example, the transverse granularity of the electromagnetic calorimeter can easily be made finer than that of the hadronic section, and the number of depth segments is unrestricted. The same tile/fiber technology can be used to insert "pre-radiator" and shower-max "strip" detectors into the stack.

2 Advantages of Tile/Fiber

The tile/fiber approach shares many of the features of conventional scintillator tile/wavelength shifter bar calorimetry. These include the "natural" sampling geometry of a scintillator/absorber stack, low cost, a very small "constant term", and a stochastic resolution which is easily tunable by varying the sampling density. This geometry has an established performance in collider detectors. In addition, the tile/fiber technique holds a number of advantages over waveshifter bar readout:

Firstly, the optical segmentation is independent of the mechanical segmentation. In conventional WLS-bar readout, the positions of the readout bars must be placed on the mechanical "cracks" between calorimeter modules. When one contem-

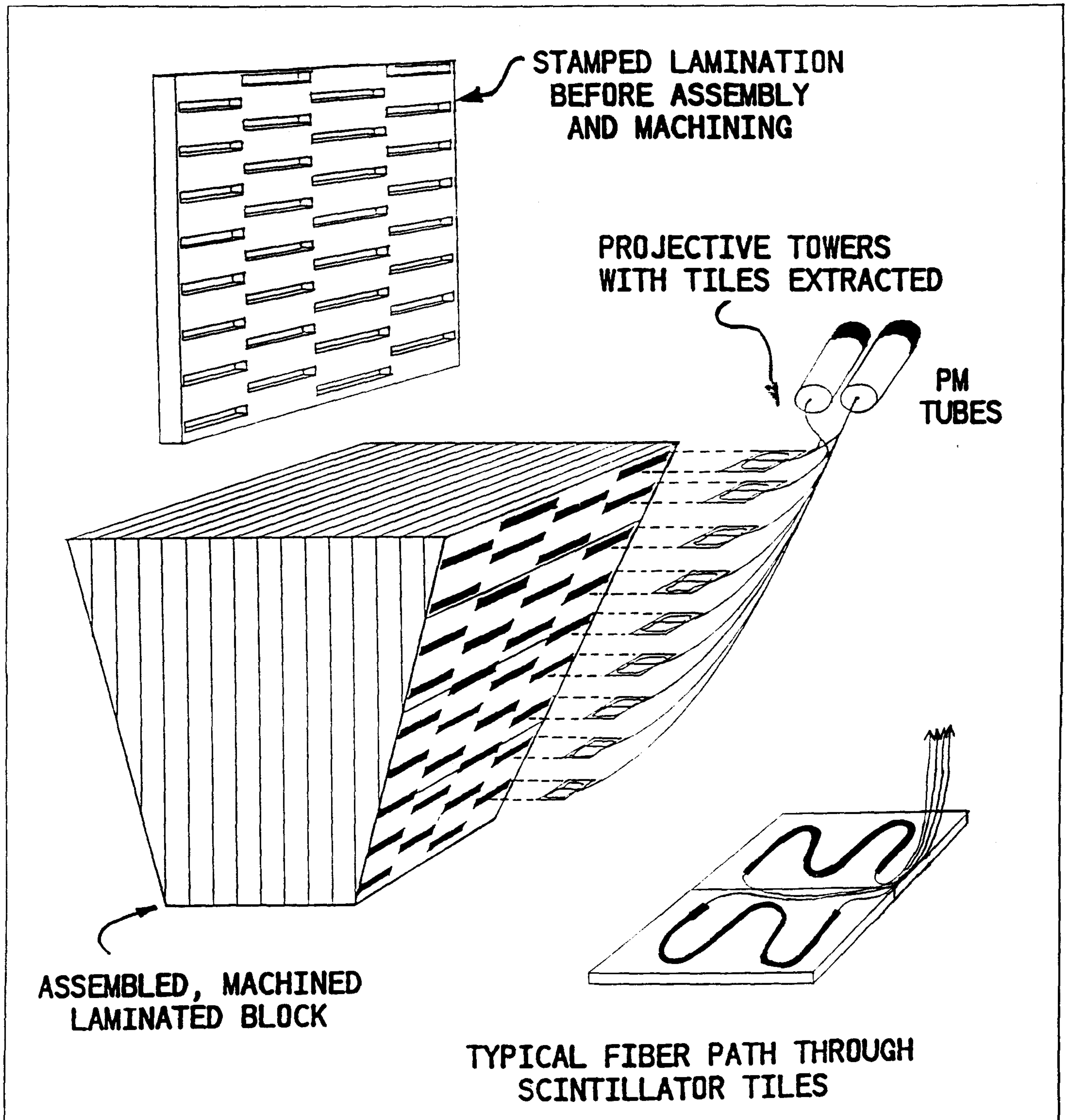

Figure 1: Schematic Scintillating Tile/Fiber Calorimeter. Projective towers are formed by stacks of scintillator tiles. Each tile is read out by a waveshifting fiber imbedded in it, which is then spliced to a clear readout fiber that carries the light to an external phototube.

plates calorimeters with the $\eta - \phi$ segmentation of a typical SSC or LHC detector, one sees that conventional WLS-bar readout will result in several hundred (or more) mechanical subassemblies. In addition, it is very difficult to produce a credible design for a finely segmented endplug calorimeter. With tile/fiber readout, the optical readout path need not coincide with the edges of each tower, and it is possible to place many optical towers in a single mechanical module.

The size of the optical "readout crack" is much smaller in a tile/fiber design, typically $< 0.5\%$ of the tower area vs. several percent of the tower area for WLS-bar readout. Furthermore, the bundle of optical readout fibers can easily be made non-projective, so that neither the average response nor the resolution of the fig.calorimeter will suffer in the vicinity of the readout bundle.

Our ability to reliably splice to a clear readout fiber avoids one of the nagging difficulties of conventional WLS-bar readout, namely the "hot spot" in the response of the calorimeter caused by Cerenkov light from EM showers in the WLS readout bar. The small amount of Cerenkov light which is trapped in the readout fibers has not been waveshifted and is easily filtered.

Nonuniformity of response across the face of the scintillator tiles is another of the classic difficulties of WLS bar readout. For isolated electrons this non-uniformity in response (typically 20%) has historically been mapped and corrected for. However, in the case of jets of hadrons no such correction is possible and is a substantial contributor to the "constant term" in jet calorimetry. We find that by dispersing the WLS fiber in a serpentine pattern throughout the tile, and selective masking of a high-quality reflective wrap, we can achieve achieve spatial uniformities of $\sigma = 1 - 2\%$ across the entire surface of a tile.

The light yield of the tile/fiber readout system is ~ 4 times higher than WLS bar readout. This is due primarily to the improved coupling of the scintillator light to the waveshifter, and to the long attenuation lengths in the clear readout fibers. Typical light yields are 3 photoelectrons per MIP per 2.5mm plate, using a 1mm readout fiber 2m in length. This factor of ~ 4 can be used in trade for a number of items. One can reduce the diameter

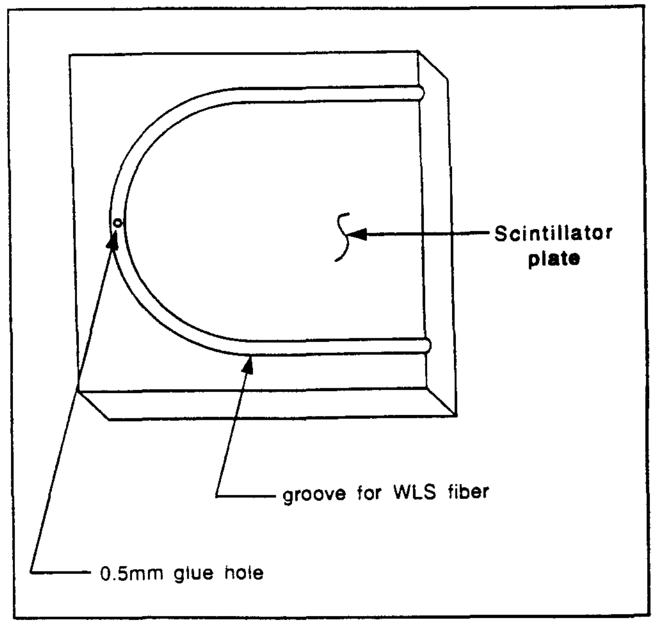

Figure 2: Scintillating Tile/Fiber Assembly

of the readout fiber, thereby further decreasing the size of the readout bundle. Alternately, one could switch to more heavily quenched scintillator and shifter dyes with faster decay times but lower light yields. The same result can be achieved by passive clipping of the pulse from the PM tube, a procedure which shortens the pulse but effectively throws away photoelectrons. Finally, one can entertain the notion of using an extremely long ($\sim$7m) readout fiber in order to remove the phototubes and electronics completely from the detector. At present we are keeping this factor as a safety margin in the calorimeter designs for the CDF endplug and the SSC prototypes.

Another advantage of the tile/fiber design is that the optical cavities are small (<1ns collection time). This yields a rapid optical pulse for which the time constant is determined mainly by the decay time (3-10ns) of the green waveshifting dye. The time dispersion of the readout fiber bundle is also considerably smaller than that of a conventional readout bar, since the cosine of the trapping angle in a typical plastic fiber is 0.95.

The radiation hardness of the tile/fiber design is enhanced with respect to WLS-bar readout schemes due to the shortness of the optical paths for the blue (unshifted) scintillator light. As is well known, radiation damage in scintillator plastics affects the shorter wavelengths first – the plastic turns brown. Transmission of green light is relatively unaffected until much higher doses. Thus, a tile/fiber calorimeter in which the blue light travels 1-2cm before collection will remain usable a much higher radiation dose that a WLS-bar readout calorimeter in which the collection distance for blue light is 10-20cm.

3 Tile Production Techniques

The basic tile unit (fig.2) is composed of a scintillator plate of dimensions typically 6x6 cm (the pad size of the tower) with a "U" shaped groove formed in it. Tile shapes can be either rectangular for use in a barrel calorimeter, or keystone shaped for en endcap design. Inside the U groove is a wavelength shifter fiber (approximate length of 12 centimeters) spliced on each end to clear optical fibers (length about 3 meters) that carry the light out to phototubes. The construction of a tile unit then consists of 3 principal operations: building the spliced fiber; manufacture of the tile; and gluing the two pieces together.

The tile pieces are laser cut from plates of the bulk scintillator. The "U" groove of size 1x1 mm is also laser milled by using the beam at a lower power. The fiber is then loaded into the groove, and tape is applied to the top surface of the tile to seal the fiber into place. Glue is then injected into the cavity formed by the "U" groove and the tape, using a 0.5mm laser-cut hole through the back side of the plate. This procedure eliminates air bubbles in the glue joint and generates a very reproducible optical connection between the tile and fiber. After the tile units are formed, the edges of the tiles are painted white with optical white paint.

First round prototyping (with Laser Services, Westford, MS) have been very successful, generating edge cuts and grooves which are better than can be obtained by diamond fly-cutters. Second round prototyping of 100 tile sets for test beam calorimeters are undergoing assembly and testing.

The spliced fiber are constructed by heat-welding wavelength shifter fibers to clear fibers. The techique that we have developed[4] is as follows (fig. 3). Cut the ends of the fibers to be spliced at approximately right angles, using a razor knife or similar tool. Insert the ends of the fibers to be joined into a glass capillary tube of ID equal to the OD of the fiber. A small coil then heats the tube to about 200°F for approximately 10 seconds. At this point, the fibers have melted together and fused. As the fibers cool, the differential contraction of the fibers cause them shrink away and release themselves from the glass tube. Initial studies of this simple technique are surprisingly successful: We have made splices with transmission of 95% with splice-to-splice variation of about 2%.

The tile uniformity is measured in a computerized test fixture. A 1 milliCurie collimated Sr^{90} source illuminates the tile, and the average current is read out for various positions on the tile surface. A computer controlled XY table drives the tile around the source. The source is collimated to $\sigma \sim$ 2mm in order to match the shower size in an EM calorimeter. The response map so generated is used to calculate a correction mask pattern, which is stored in the computer until needed. Tiles that fall outside of selection criteria are discarded. Fig. 4 shows a typical response map for an uncorrected tile. The scans are in the direction crossing the fibers (Y). Each scan line represents a scan at a different X. The fibers generate peaks in light yield which are visible in the figure. These peaks are suppressed by a "masking" technique.

Tiles that do not have a completely uniform response can be "flattened" by a masking technique. The tile is wrapped in a reflective metal foil, with the foil blackened in areas where the tile response is too large. This mask pattern is used both correct for both the spatial variations and the piece-to-piece variations in the overall light yield of the tiles. The operating principle of this technique is as follows: Depending on the doping of the scintillator tile, the conversion distance of UV primary scintillation light to blue light is of the order 1mm. Therefore UV light generated near the surface of the tile has a large probability of escaping before being shifted. Placing a UV reflecting surface near the tile will cause the escaping UV light to be reflected back into the tile, which produces a local increase in the light yield. Conversely, a UV black

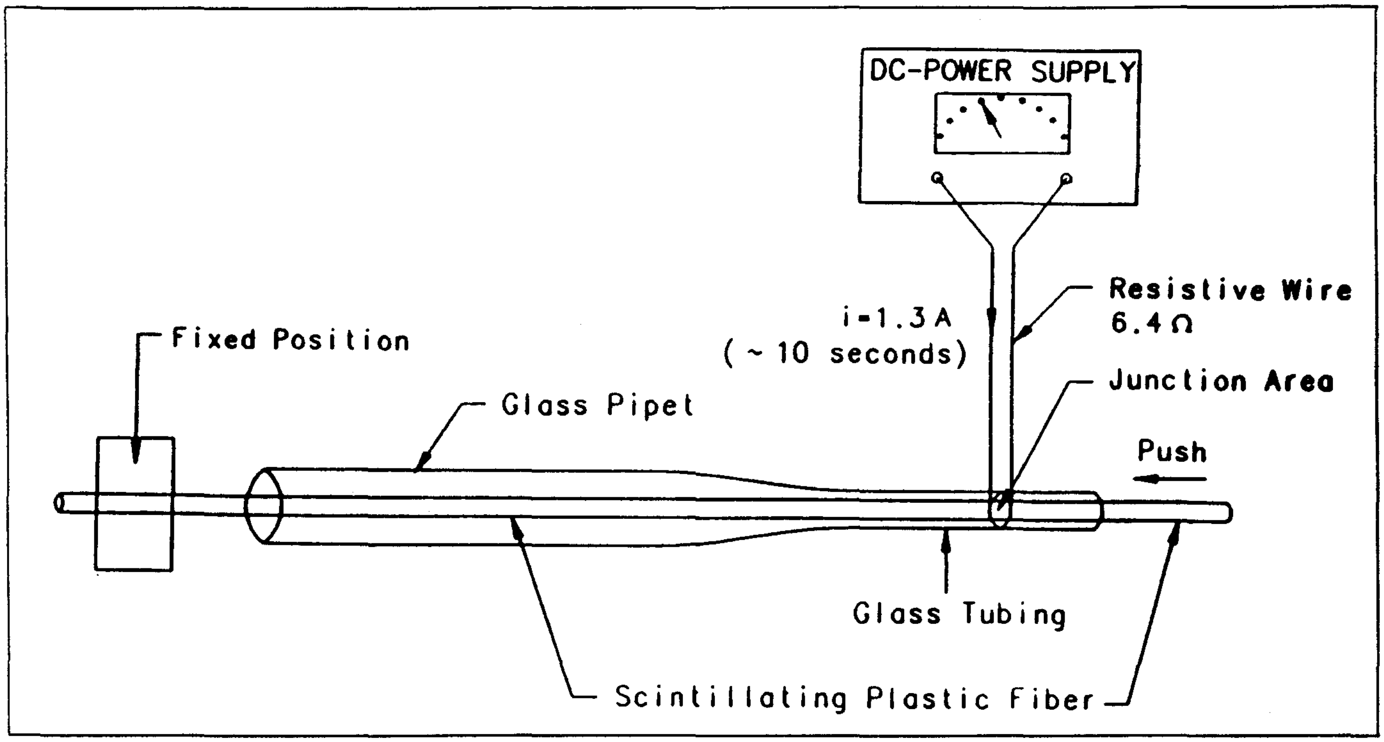

Figure 3: Method for Splicing Plastic Optical Fibers.

material will cause a local suppression in the light yield. With the polystyrene scintillators that we normally use, there is about a 20-30% dynamic range in the correction, which is sufficient to flatten out any observed nonuniformities. The correction mask of dark patterns is generated using the measured tile response map. This correction mask is applied to a metalized foil[5] with a conventional laser printer.

The resulting mask flattens the tile response to the σ =1-2% level.

4 Choice of Absorber

The key issues in the choice of an absorber for an SSC calorimeter are energy resolution, cost, speed of response, magnetic properties, mechanical convenience, and neutron albedo in the central tracking volume. The spatial uniformity of the tile/fiber readout allows us to consider thinner (1-3 mm) scintillator tiles than would otherwise be practical with conventional tile calorimetry. This allows us the freedom to design a high resolution, compensating calorimeter using lead, iron, uranium, or a wide variety of combinations of the above.

For the electromagnetic calorimeter, we view the resolution as the key parameter. Compensation properties are secondary since it is impossible to deposit a large amount of hadronic energy in the EM calorimeter (unless of course the incoming hadron(s) charge-exchange in the EM calorimeter, in which case the energy is still accurately measured in the EM calorimeter). Thus, for both the CDF upgrade and for SSC prototype work we are following the common choice of Pb as the EM radiator. We choose a Pb:Scintillator ratio of 2:1 by volume, which yields an adequately compensating e/h response ratio of ~1.1. The resolution of the EM calorimeter will be determined primarily by economic considerations (number of samples in depth). We anticipate Pb radiator thicknesses of 0.5cm to yield energy resolutions of $15\%/\sqrt{E}$, so that at energy ranges of interest at the SSC the 1-2% constant term will dominate the resoluton of the EM calorimeter.

At the SSC, the speed of response is one of the key issues in the design of a hadron calorimeter.

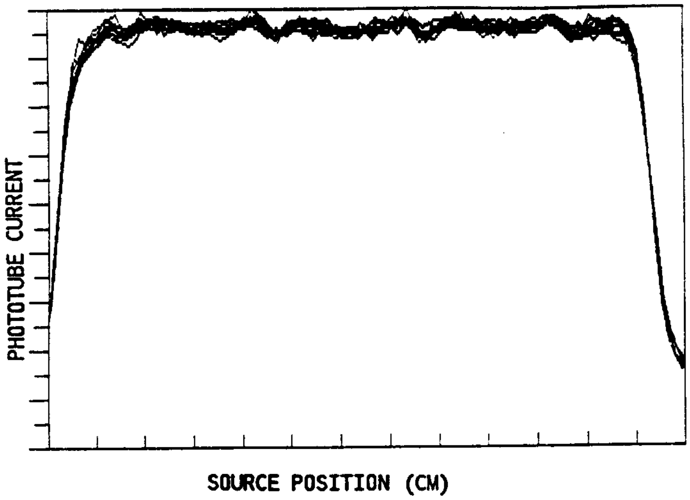

Figure 4: Uncorrected Uniformity of Response of a Typical Scintillating Tile/Fiber Assembly. After a correction mask is applied, the uniformity of response is σ =1-2%.

Generally speaking, there are two mechanisms for achieving compensation in a samplng calorimeter: The first of these (neutron interactions in the scintillator) yields a slow signal which arrives 50-100ns following the primary energy deposition. In addition to being slow, this neutron "timing tail" fluctuates on an event-to-event basis. This makes it impossible to clip it away in the same manner as the scintillation timing tail, which is purely exponential and is reproducible from pulse to pulse. The second mechanism [6] (suppression of the EM response by alternation of high-Z and low-Z materials) is essentially instantaneous. Clearly, to obtain the fastest possible time response, one would like to use a system with a very low neutron yield and which achieves compensation largely through the suppression of the EM response. The relative neutron yields from U, Pb, and Fe are in the approximate ratio of 5:2:1, suggesting iron as an extremely fast hadron absorber. It is interesting to observe that an iron calorimeter, with its very low neutron yield, will create the smallest neutron flux in the the central tracking volume. Iron has other well known advantages in terms of cost and mechanical convenience.

We are prototyping an iron-dominated hadronic calorimeter with the goal of clipping the phototube pulse back to baseline, and achieving approximate compensation, inside a 16ns gate (one crossing time at the SSC). The prototype takes advantage of the ability of the tile/fiber techique to read out large, thin scintillator plates in order to obtain the proper Fe:Scintillator ratio (various computer codes predict the compensating mixture of Fe:Scintilator is between 10:1 and infinity). If necessary, the e/h response will be tuned by the insertion of a small amount of high-Z material (probably lead) into the stack. The purpose of this material is to convert the low-energy γ's from EM showers. Insertion of this material immediately upstream of the scintillator will increase the EM response while leaving the response to MIPs and neutrons essentially unchanged. Conversely, insertion of the lead downstream of the scintillator will suppress the EM response. A similar suppression of the EM response can be obtained by "cladding" the scintillator in a low-Z material (such as aluminum) which will not convert many of the low-energy γ's but will serve to range out the secondaries from γ's which have converted in the iron and thereby shield the scintillator from this EM energy. If some combination of these techniques is successful at reducing the e/h significantly below 1.0, we will then add additional hydrogenous material ("dead plastic") into the stack in order to absorb more of the slow, unwanted neutron signal. These (and other) compensation techniques are being studied for iron hadron calorimeters in the FNAL test beams in 1990-91.

5 Staggered Plate Calorimetry

We have developed a unique mechanical structure and manufacturing technique which is being tested on our SSC hadron calorimeter prototype. The basic concept (figs. 1 and 5) is to produce each "wedge" of calorimetry in the central barrel as essentially a solid, keystone-shaped block of iron with a large number of slots cut into it. The slots, which accept the completed scintillator tile assemblies, are staggered in adjacent towers in η so as to maintain the mechanical integrity of the block.

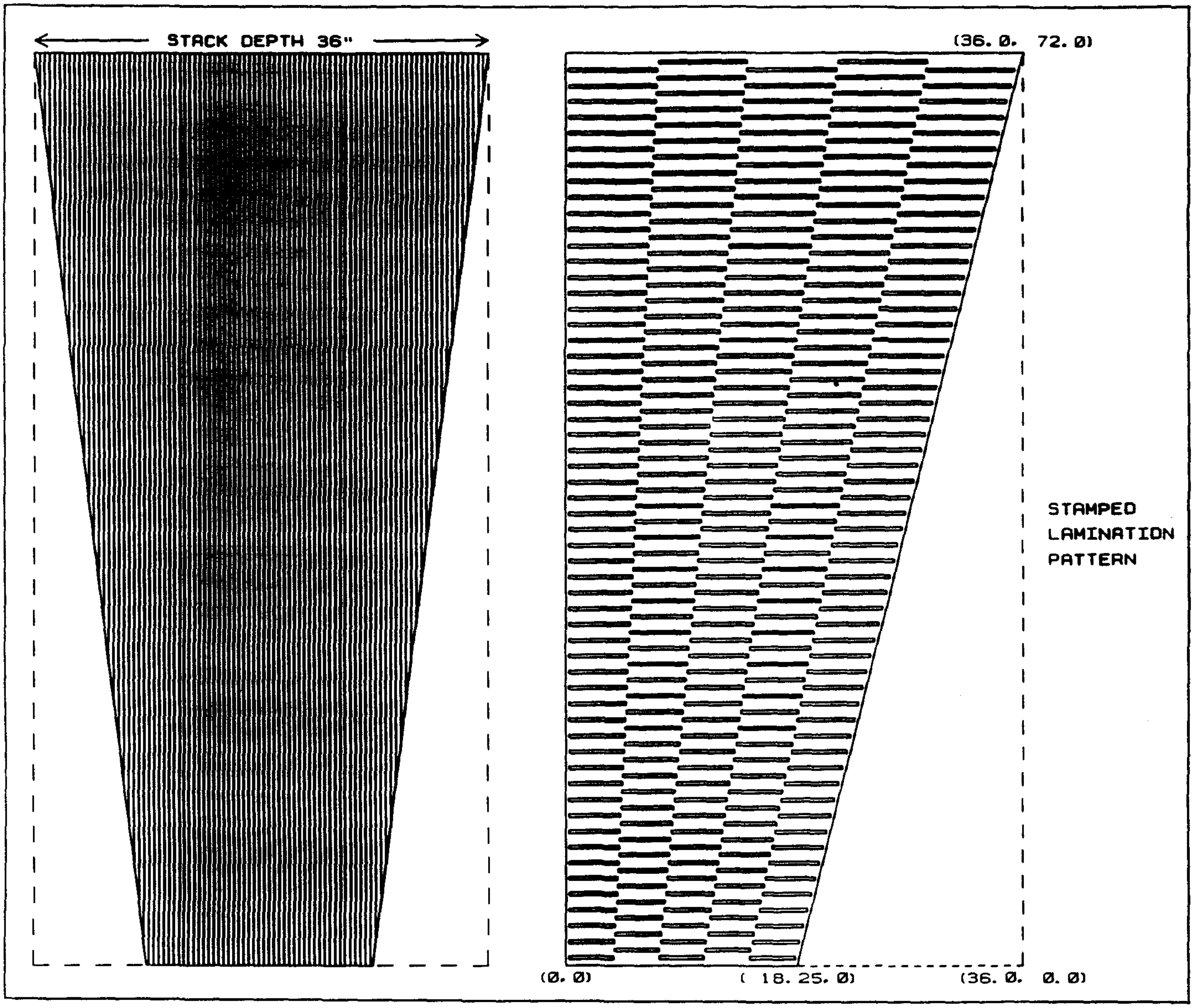

Figure 5: Iron Lamination Structure of Prototype Scintillating Tile/Fiber Hadron Calorimeter. The right-hand side is a view of a single lamination, into which slots have been punched to generate the projective towers in η. The lefthand side shows the assembled stack.

The mechanical loads are bypassed locally around each of the scintillator tile slots, and there is no need for large semi-projective structural members to "reach around" the stack to provide mechanical support. In this sense, this design has absconded with one of the main attractive features of "spaghetti" calorimetry, namely that the finished module is a single self-supporting structural unit with no "cracks" needed for mechanical support.

Several fabrication techniques were investigated for the iron block with the slots in it (fig. 5), including casting, water jet cutting, and welding. The method chosen was to laminate the piece together out of a large number of stamped plates, in the manner commonly used to produce large accelerator magnets and industrial transformer cores. The pattern of slots (which determine the pattern of towers in η) is punched into each lamination by a numerically controlled punching machine. The laminations are then stacked and held together by a combination of B-stage epoxy and seam welding. A final machining operation grinds down the faces of both sides of the keystone block, in order to guarantee that the pieces fit together precisely when the complete arch of calorimetry is assembled. Small, non-projective grooves are machined in the side of each block to accept the readout fiber bundles for each tower. The final cost of iron structures manufactured by this method is in the range of $0.75-$1/lb.

The last step in the assembly of the calorimeter modules is the insertion (fig. 1) of completed tower assemblies of scintillating tiles into the absorber block. Prior to insertion, each tower assembly will be tested for light yield and uniformity, and the complete assembly will be annealed in it's final configuration to remove internal stresses on all tile and fiber components.

6 Application to CDF Endplug

The tile/fiber system has been presented to the Fermilab PAC as an upgrade proposal to replace the gas proportional calorimetry of the CDF endplug. In this application the tile/fiber system has the unique advantage that the assembled planes of scintillator can be inserted into the gaps of the existing absorber structures, in place of the existing gas proportional chambers. The projective towers are formed by the optical segmentation of the tiles within each scintillator plane.

The clear optical readout fibers from each tile are led to phototubes outside of the calorimeter along the path currently taken by the electrical cables of the gas calorimeters. Thus the small size and flexibility of the readout fibers allows us to retain the absorber structures which were originally designed for use with the gas proportional chambers, thereby avoiding mechanical construction costs, the necessity to re-map the magnetic field, etc. In addition, even in the endplug geometry each tile can be made quite uniform, with an rms variation of light yield with position 1-2%. The spatial uniformity of this technique provides benefits to both electron and jet physics.

Prototypes of both EM and Hadron calorimeters are being evaluated in the current (spring '90) test beam at FNAL, so that results will be available in time for production decision later this year.

References

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[2] The CDF Collaboration, "Proposal For an Upgraded CDF Detector ", Draft: May 1990, Preliminary Version, CDF/DOC/PUBLIC/1172

[3] "Expression of Interest by the Solenoidal Detector Collaboration to Construct and Operate a Detector at the Superconducting Super Collider", submitted to the SSC laboratory, Dallas TX, June 1990.

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[5] Obtained from Graphic Arts Systems, inc. Cleveland, OH USA

[6] This effect is also discussed in the contributions from the SICAPO collaboration to these proceedings.