# Scintillation tile studies for sPHENIX at UTFSM

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## 1 Introduction(sPHENIX HCal)

The conceptual design of the sPHENIX Hadronic calorimeter has been the work of many people since January, 2012 when work began on the Major Item of Equipment (MIE) proposal submitted to BNL on July 1, 2012. The HCal is an hadronic calorimeter designed to trigger on and identify hadronic jets and to measure their energies, and to assist with electron identification in the sPHENIX EMCal (by measuring energy leaking from EMCal to the first section of the HCal). In the final configuration the total energy deposited by showering particle will be measured by summing up the digitized data from EMCal and all HCal section (located inside and outside superconducting solenoid).

In the base option the steel plates (nonmagnetic inside solenoid) are separated by an 8.5mm constant thickness gap housing the active scintillating tiles. The thickness of the steel plates grows from smaller to larger radii resulting in visible energy fluctuations depending on shower realization. Normal longitudinal fluctuations in the shower development are enhanced by the fact that particles entering the calorimeter through gaps filled with the scintillating tiles will travel an extra few cm without crossing the steel absorber. In a relatively thin tilted plate calorimeter system with depth dependent sampling fraction such enhanced fluctuations may lead to a large value of the constant term in the energy resolution and large non-Gaussian fluctuations in energy leakage out the back of the calorimeter.

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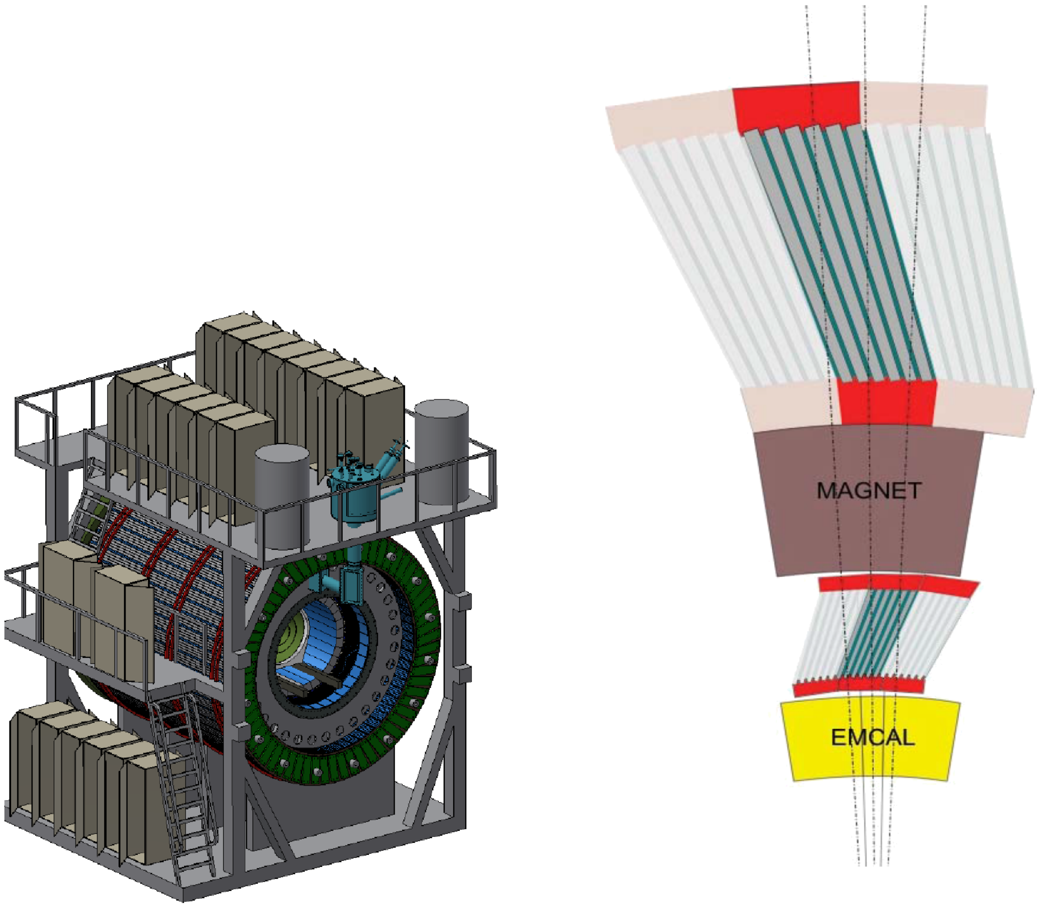


(a) sPHENIX detector

(b) sPHENIX Calorimetry (EMCal, HCal Inner and HCal Outer)

Figure 1: sPHENIX detector and Calorimetry

Each segment of the HCal is constructed of 320(64x5) tilted steel plates and logically and readout segmented into 64x24 detector towers The active elements in every tower are scintillating tiles with embedded wave-shifting fibers spanning 0.1 units of rapidity ($\eta$ is used in physics as a measure of the polar angle, where $\eta = -ln(tan(\theta/2))$, where $\theta$ is the polar angle and $ln$ is the natural logarithm) . The physics goals of the experiment require an acceptance $|\eta| < 1.1$, which corresponds to a polar angle of $36.82°$ and no compromise in detector performance within $|\eta| < 1.0$, which corresponds to a polar angle of $40.39°$. There is a total of 2112 logical detector elements (towers), in HCal each longitudinally segmented into Inner and Outer sections.

## 2 Mechanical Design of 2013 and past R&D

The mechanical R&D of the HCal design began over two years ago with the dessign and construction of a relatively small HCal prototype (see Figure 2) which was built in US industry and instrumented with scintillating tiles purchased from long time PHENIX partner in Russia (Uniplast, Vladimir, Russian Federation).

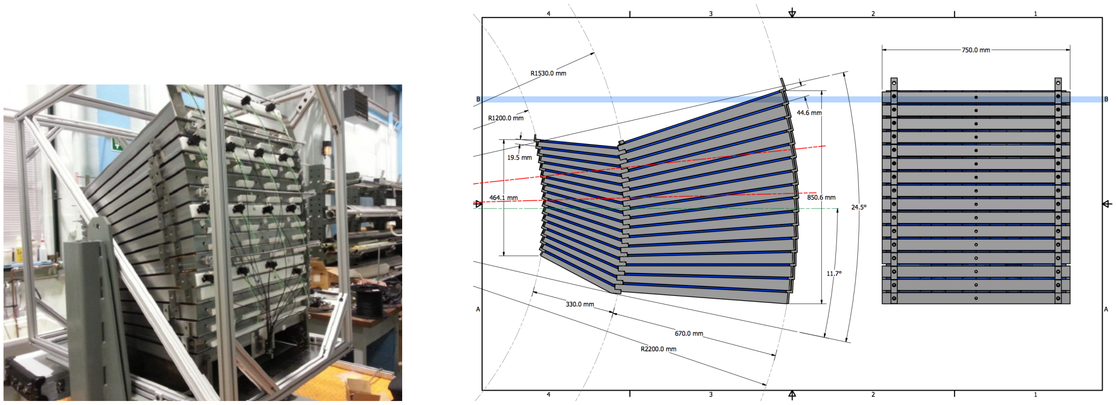


Figure 2: The sPHENIX HCal prototype of 2014

The FNAL Test Beam experiment T1044 exposed a prototype EMCal (consisting of tilted W plates and scintillating fibers) and the prototype HCal (two sections of tilted steel plates and scintillating tiles with embedded fibers) to beams of electrons and hadrons (mostly pions). In the test beam the prototypes were mostly operated as two standalone detectors. The corresponding data were analyzed independently and appropriate results have already been presented to the sPHENIX collaboration. The HCal measurements were found to be in good agreement with simulation.

## 3 Mechanical Design of 2016 and ongoing R&D

The HCAL active medium are 7mm thick scintillating tiles, as shown in Figure 3. In the 2014 design two ends of the fiber were exiting separately and had long tails used to passively add light collected in fibers embedded into individual tiles (4 tiles per tower). The base tile material is polystyrene doped by the mix of 0.01% PTP and 1.5%POPOP.

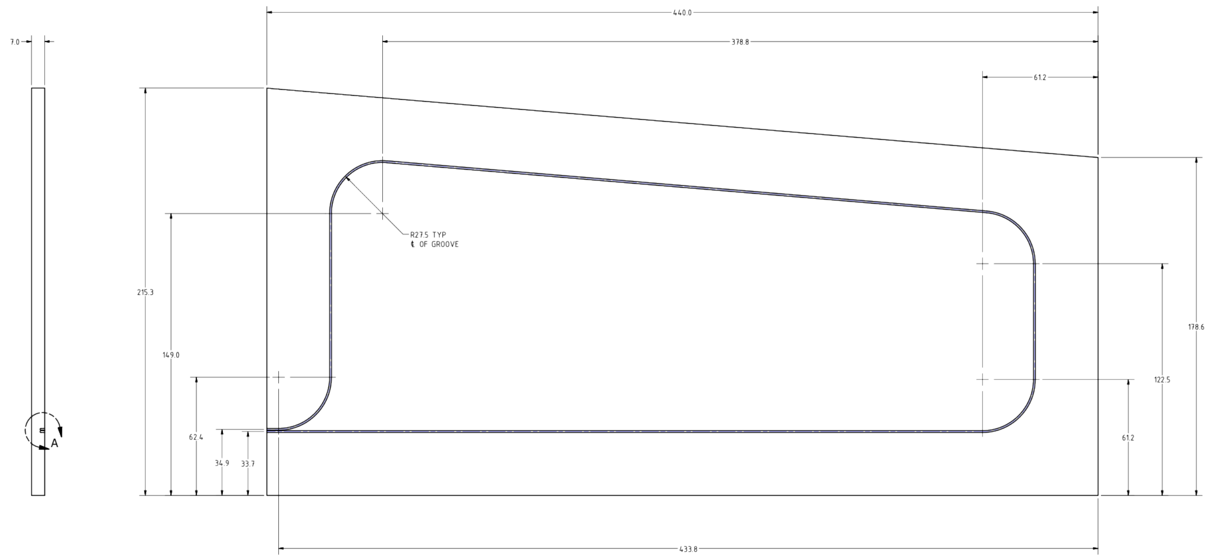


Figure 3: Engineering drawing for Inner HCal scintillating tiles.

The Inner and Outer tiles are of different lengths and shaped differently depending on rapidity resulting in a nearly perfect pointing towards the collision point in rapidity space. The scintillating light produced in the tiles by ionization due to charged particles stays inside the tile and is reflected diffusely by a white reflective coating and reflective tile wrapping. The light is absorbed by a wave-shifting fiber embedded into grove cut in the scintillator body.

Experience accumulated during test beam effort of 2014 have shown that the passive tile light summation by bundling fibers outside of protection provided to tiles by still plates was unsafe solution. Fibers become brittle when stored for substantial time so they are easy to break, it is time consuming and damaging to fibers to glue them together almost unconstrained, it is even more difficult to polish the fiber bundles in-situ with fibers from other tiles all around.

Based on this experience and on the availability of relatively cheap silicon photosensors (SiPM) the decision was made to modify the original tile design to install individual SiPM′s on every tile (one SiPM per tile) and to passively sum currents generated by photons captured in individual tile-SiPM pairs. While fiber pattern and design rules were kept largely unmodified the two ends of the fiber were now brought together to a common exit point, directed orthogonally to the tile edge, glued at a depth in tile allowing for installation of a single 3x3mm2 SiPM device centered around pair of closely packed polished fiber exits. An effort was made to chose the gap between polished fiber ends and SiPM to maximize the light spread over the SiPM surface area helping to reduce the probability of SiPM saturation resulting from two or more photons impinging on the same pixel. The gap of 0.75 mm was chosen by requiring no more then 5% variation in the SiPM response when fibers and SiPM are misaligned for 0.2mm and no more then 20% loss of the light outside of SiPM sensitive area.

Preliminary design for the enclosed coupler between fibers and SiPM is shown in Fig. 4.

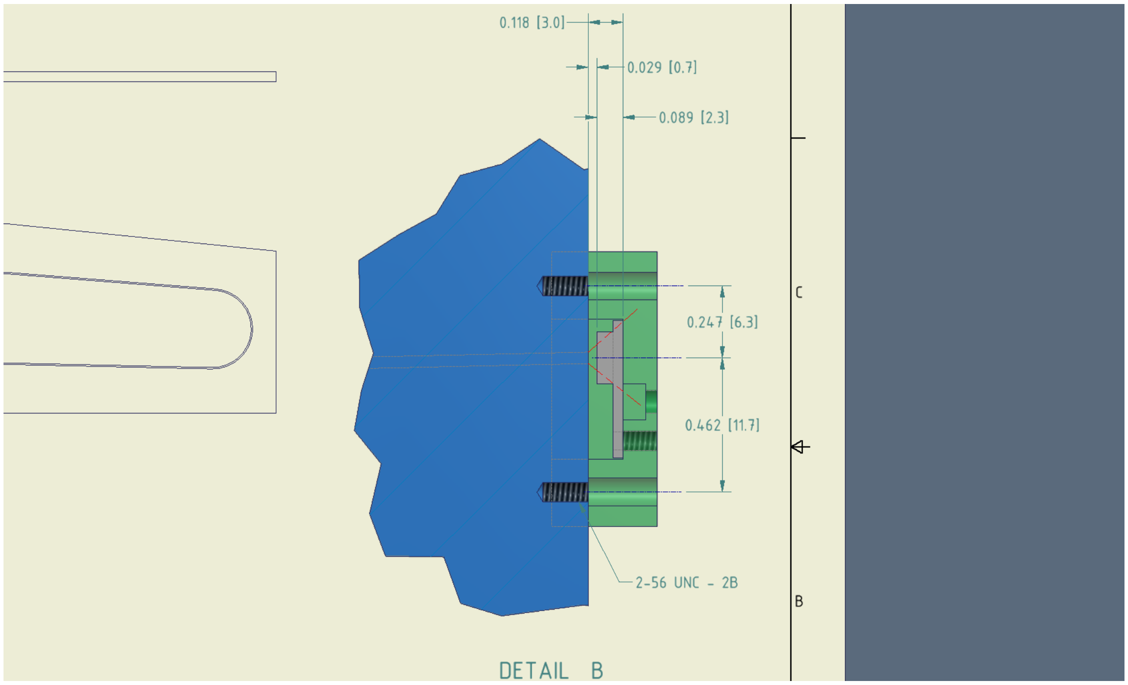
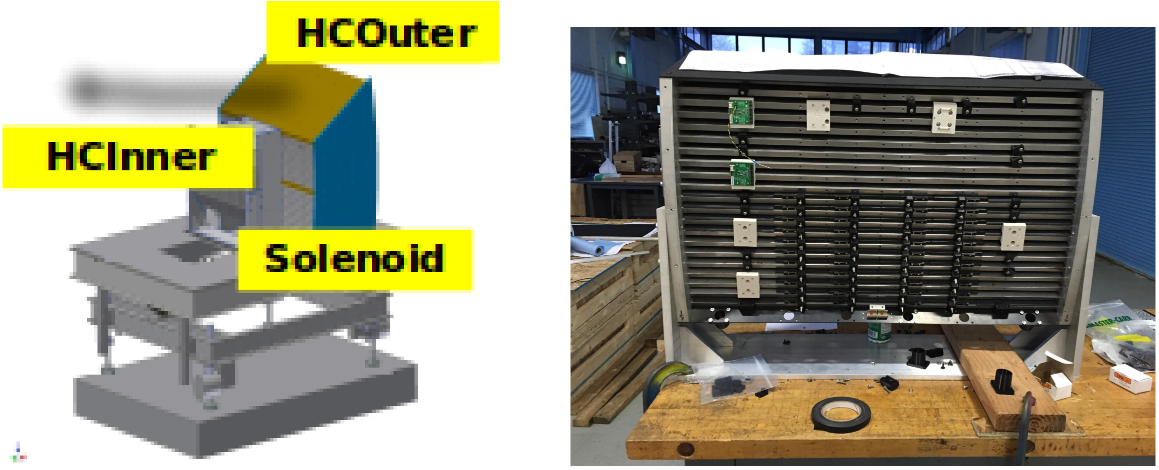


Figure 4: One possible design for the fiber to photon detector coupler.

The 2016 system HCal prototype built of similar tiles with couplers of similar design is shown as ACAD model in the left panel in Fig. 5 and is now in assembly stage at BNL. (right panel, in fig. 5).



(a) 2016 sPHENIX HCal prototype

(b) Inner section of HCal prototype in assembly stage at BNL

Figure 5: HCal prototype

With a very unusual design of sPHENIX HCal it is imperative that every component of the detector which may affect it performance be individually simulated, prototyped, tested and characterized.

## 4 R&D on the Tile Light Collection Uniformity at UTFSM

Scintillating tiles for the calorimeter are manufactured by UNIPLAST Company in Russia (Vladimir). The dry mix of polystyrene granules, PTP and POPOP melted and extruded by extrusion machine which produces continuos band of hot scintillating plastic 25cm wide (see Fig. 6).

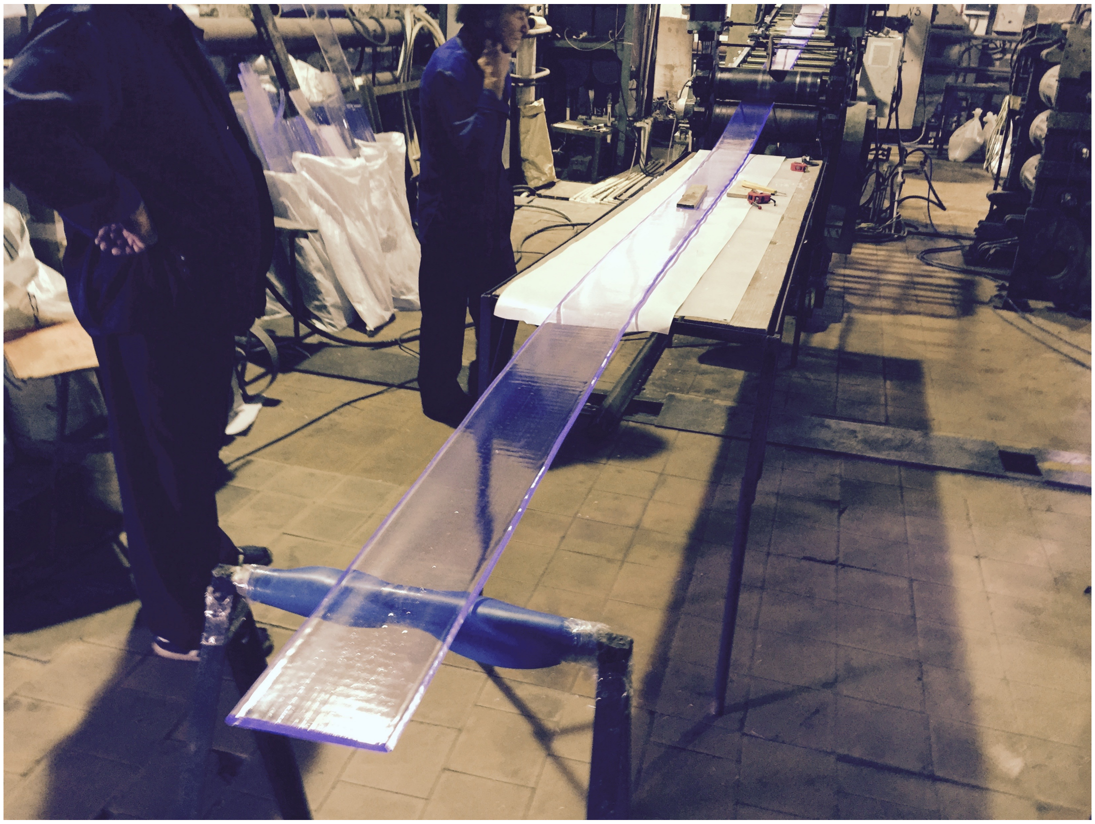
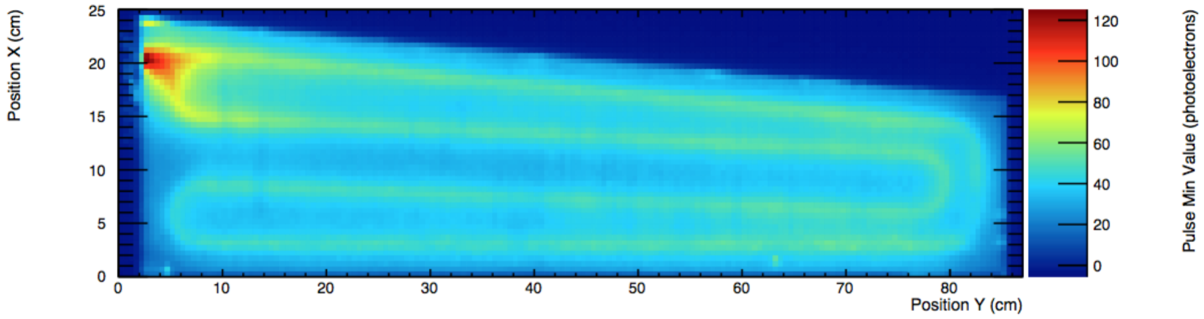


Figure 6: Scintillator band extrusion

The scintillator is cut into 2m long pieces which are inspected for defects and miscolorations and, if this low level control is passed, mechanically machined into the tiles according to the drawings. Tiles are further exposed (in a bath) to the mix of aromatic solvents resulting in the development of white diffuse reflective coating (average thickness 0.05mm) over the whole tile surface. This process removes micro nonuniformities normally present on the surface of extruded plastic thus decreasing aging and improving tile ability to withstand preasure without crazing. It also enhances the efficiency of light collection in tiles with embedded WLS fibers. Coated tiles are grooved, then WSF are embedded and glued using optical epoxy (EPOTEC-301) with special care given to fiber positioning at the exit from tile. Fibers are cut at the tile edge and hand polished.

A number of tiles produced at UNIPLAST for 2016 HCal prototype were tested at BNL(NY, Long Island) and CSU (Colorado, Boulder). Measured light yield ($\sim$1000 pixels/GeV) was found perfectly consistent with required stochastic term to energy resolution and allows for measurements of cosmic muon signals in calorimeter with signal dynamic range of 50GeV and 14 bits digitization what is paramount for calorimeter calibration. The light yield was found very stable tile-to-tile.

Detailed measurements of tile uniformity were made at CSU with collimated LED moved over the surface of unwrapped tile under computer control. A typical response map measured exposing clear (no fiber) side of the tile to LED light (through the coating) is shown in Fig. 7.



We scan in 0.5 cm increments in both directions
We scan 50 rows and 174 columns, which is slightly bigger than the tile itself

Figure 7: Map of the tile response to LED light measured at CSU (Colorado).

Tile looks uniform within 20% everywhere except in proximity of fiber exits where the signal in response to LED pulsing is at least x3 higher then average over the tile.

The observed increase in the signal value may have multiple reasons in particular:

- light from the bulk scintillating material reaches SiPM before it is stopped by the fiber or by coating (polishing fibers cut closely to the tile edge damages the coating in the vicinity of fiber exit);
- light escaping fiber cladding. We are intentionally using single clad fibers to allow the cladding light to escape and be absorbed in bulk scintillating material. Unfortunately it stays within narrow cone around fiber and similar to the bulk light may reach the SiPM through partially transparent coating around fiber exit.

Both components are important mostly in the vicinity of the fiber exit (blue light from scintillator and green light from WLS fiber are absorbed within few cm from the point where it is emitted or enters the bulk material).

To explore the validity of the explanation and to test one particular mitigation scheme, few Inner HCal tiles were built in the experimental lab of the UTFSM using scintillating material machined and coated by UNIPLAST.

A typical UTFSM tile ready for final wrapping is shown in Figure 8 (Inner HCal).

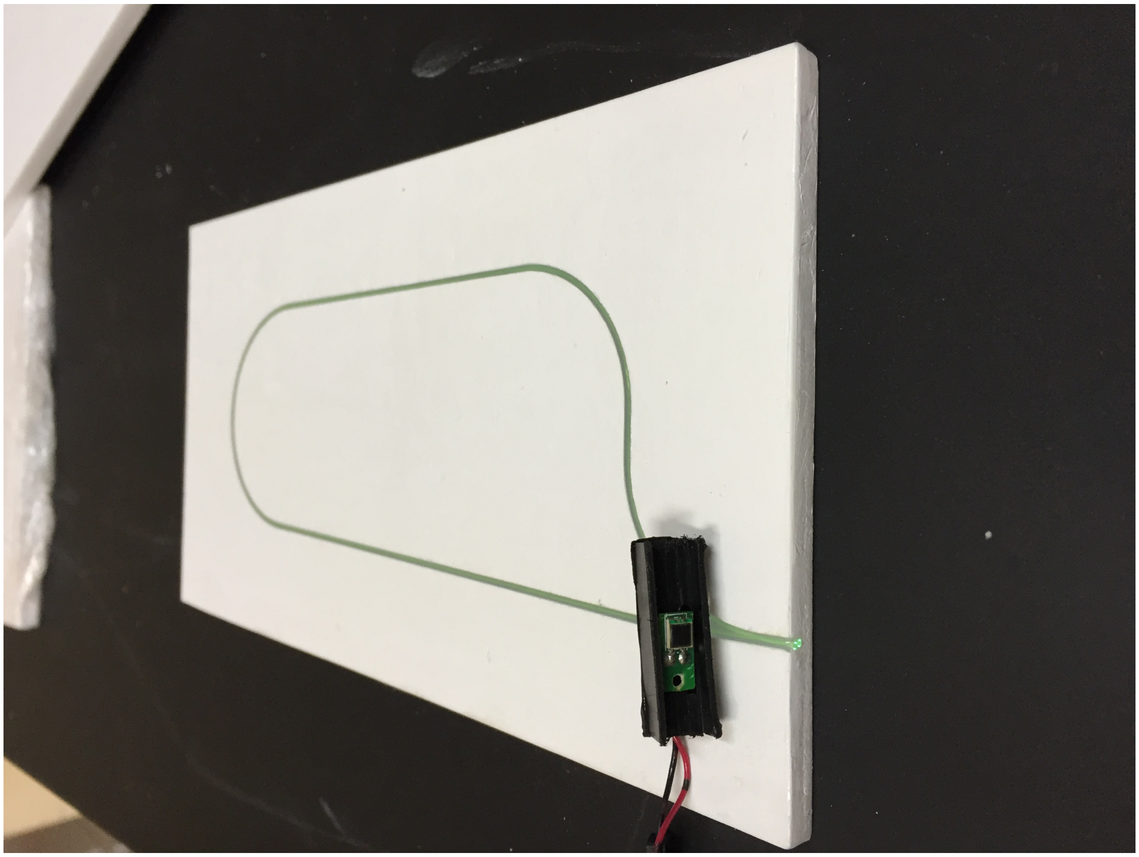


Figure 8: Production tile for sPHENIX Inner HCal section. Grooving and fiber embedding at UTFSM.

The 5mm deep recess was machined along the edge of one of the tiles at the fiber exit location. The 5mm thick black plastic light-stopper with two 1mm closely spaced holes for fiber exits was glued into recess. While embedding both ends of the fiber were epoxied into the holes in the light stopper (Fig. 9).

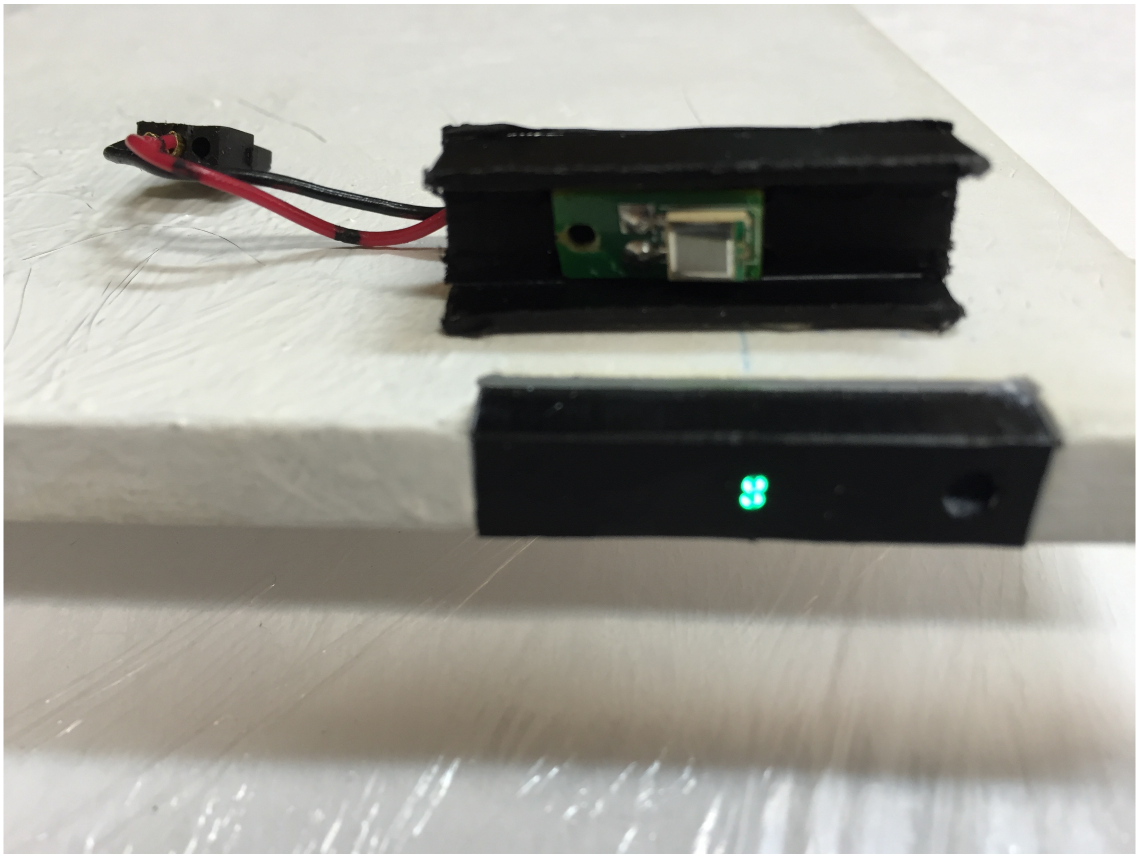


Figure 9: Production tile for sPHENIX Inner HCal section. Grooving, installation of bulk light stopper and fiber embedding at UTFSM.

Two tiles (one without light stopper and another one with the light stopper) were scanned with blue LED light source (420nm) both on clear side and on a side with embedded fiber (see Fig. 10 -scanner).

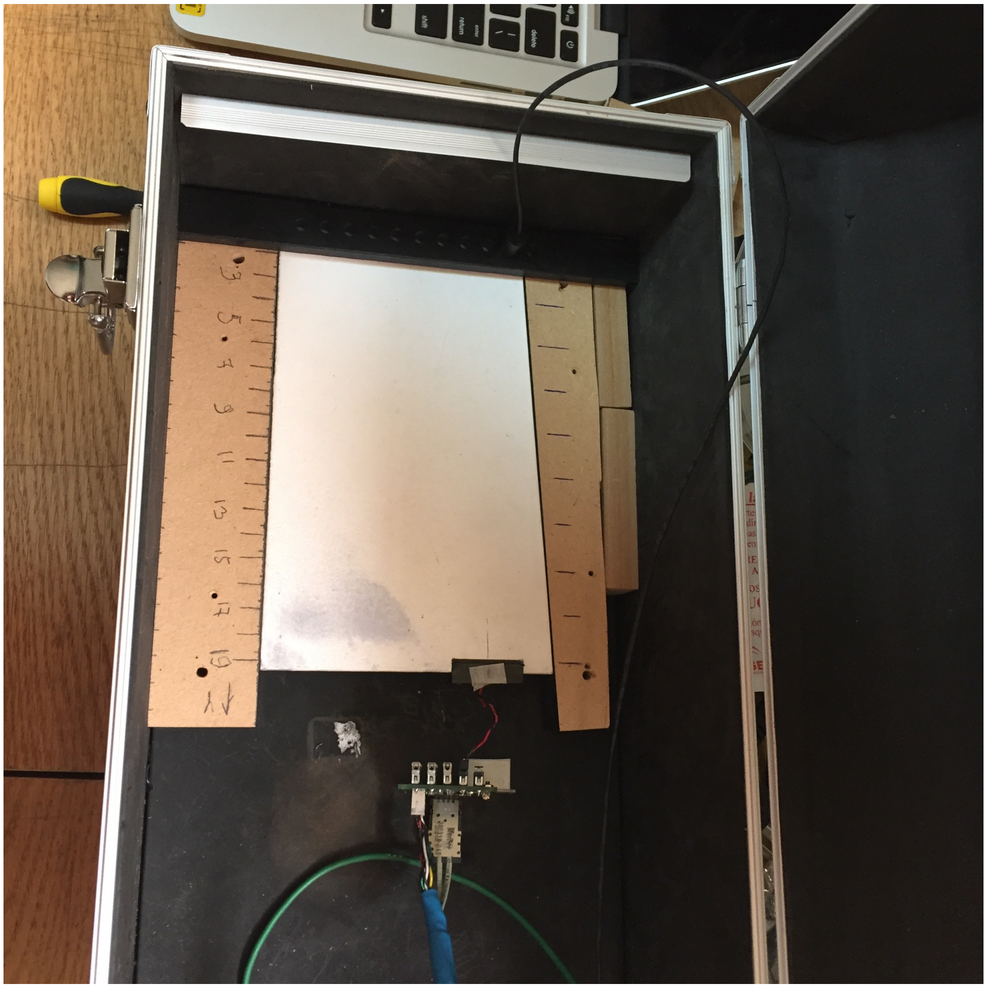


Figure 10: Tile scanner at UTFSM.

Measurements were made on a rectangular matrix of points with a step of 1cm in X (across the fiber) and 2cm in Y (along fiber). To reduce electrical pickup from LED pulsing the LED was installed in the holder outside of the Faraday cage built around tile, SiPM and preamplifier, light from LED was transported to the tile via 0.5m long clear fiber and a slew rate of LED trigger pulse was always kept below 100mV/ns. No effort was made to center LED over the fiber what resulted in somewhat unreasonable variations in the amount of light seen by SiPM when tip of the delivery fiber was close to WLS fiber (1x2cm2 cells overlapping with fiber).

We have chosen to do our measurements using single pixel scope traces to maintain the gain and repeated measurements with LED positioned over measurement points in the first Y-row to control reproducibility of data. An example of the distribution for the value of

$$dA = (Ao - At)/((Ao + At)/2) \tag{1}$$

is shown in Fig. 11 below.

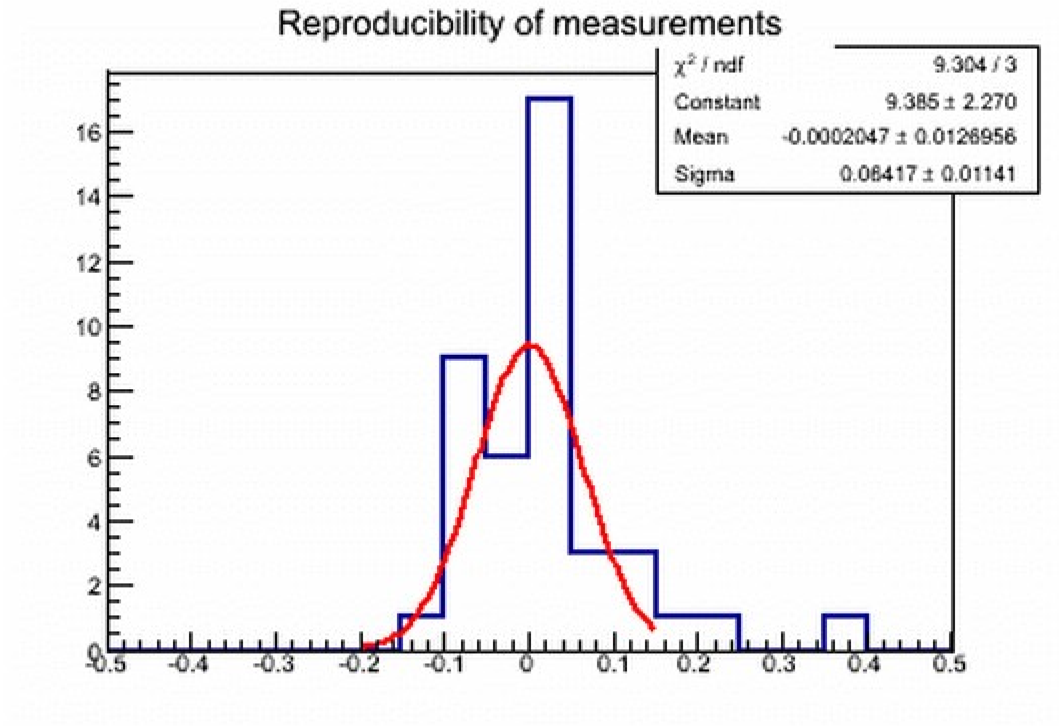


Figure 11: Comparison between measurements made in the same locations of tile before and after tile scaning.

The average difference between two measurements is centered at “0” with an RMS $6\%$ what we find totally satisfactory for all practical purposes in this work.

In what follows we always used signal amplitudes averaged over the points in the bottom row of (excluding those which were affected by direct fiber exposure to LED light) for normalization purposes. We see no difference between tile responses to LED exposure on both (clear and fiber) sides of the tile except in the close proximity to the fiber (see Fig. 12 for the tile “as designed” and , Fig. 13 for the tile with black light stopper below).

On the opposite - there are many differences between tiles. The normalized amplitudes of signals due to LED pulsing vary within x1.5 (with respect to average) in tile with a stopper and spread to nearly x4 in tile without stopper (tiles (a,c) in Fig.s 12, 13). Adding bulk light stopper clearly improves light collection uniformity along fiber length (tile (b) in Fig.s 12, 13). It does not change the clear-to-fiber sides correspondence but definitely decreases the width of the amplitude distributions measured in points outside of fiber areas (tile (d) in Fig.s 12, 13).

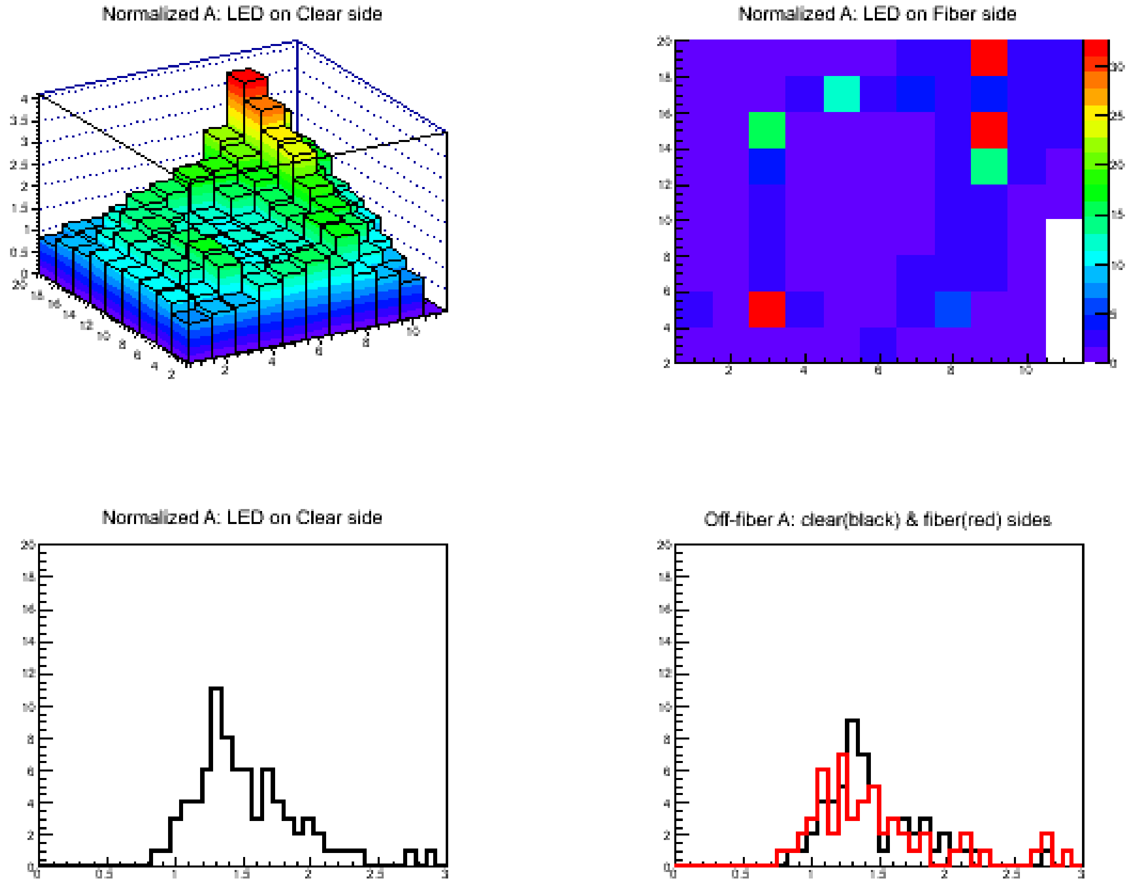


Figure 12: Map of the tile response. Tile without bulk light stopper. (a) LED exposure on a clear side; (b) LED exposure on a side with embedded fiber; (c) Normalized amplitudes measured exposing clear side of tile to LED; (d) Normalized amplitudes for clear(black) and fiber(red) sides exposure (off fiber area).

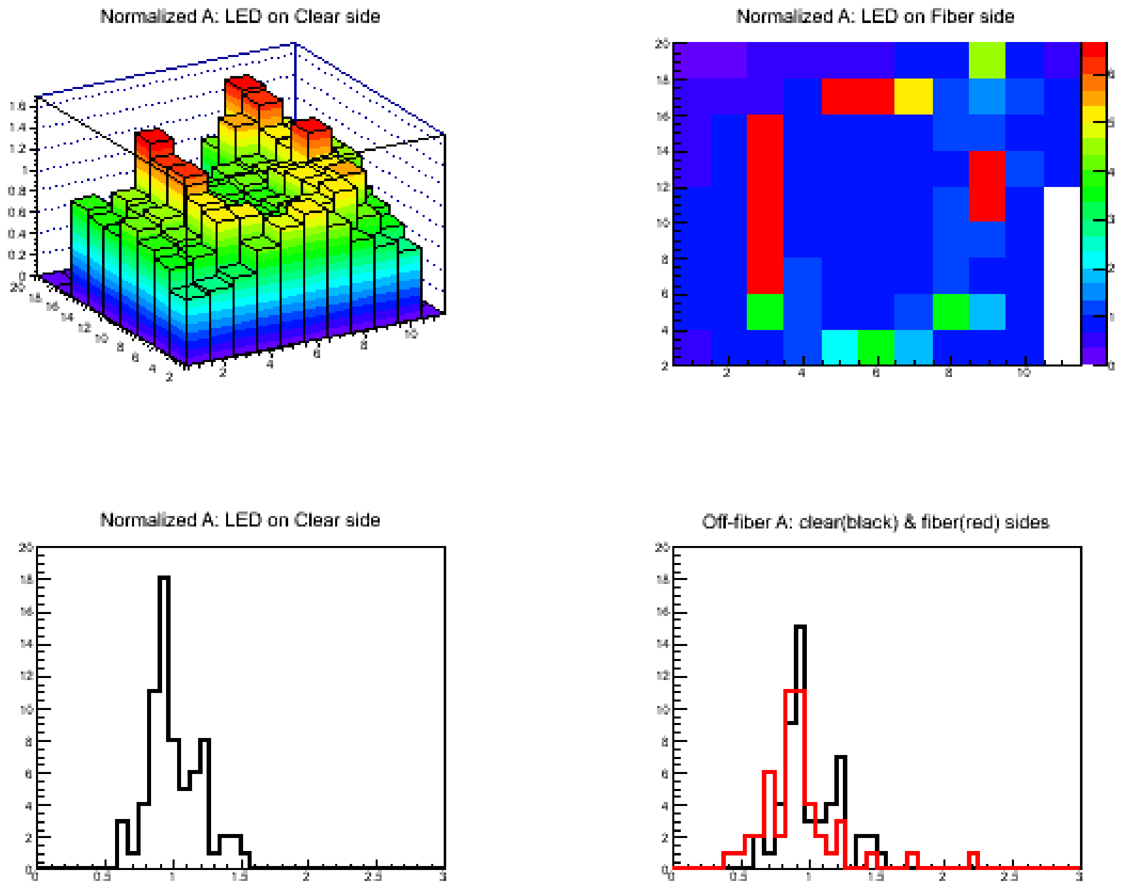


Figure 13: Map of the tile response. Tile with bulk light stopper. (a) LED exposure on a clear side; (b) LED exposure on a side with embedded fiber; (c) Normalized amplitudes measured exposing clear side of tile to LED; (d) Normalized amplitudes for clear(black) and fiber(red) sides exposure (off fiber area).

The effects which we are interesting and important for this particular research do not really include those related to direct emission of light due to scintillating light emission inside fiber or in the epoxy in the grove. The latter can′t be studied with LED, they need precision data with ionizing particles and position measurements.

To make earlier statement of improved light collection uniformity in the tile with black bulk light stopper a more quantitative in Fig. 14 we compare the tile response to LED (signal amplitudes before normalization) averaged over points at the same distance from fiber exit in the areas “unaffected” by being too close to the fiber (based on lego plots of signals measured exposing fiber side of the tile without black stopper). Affected is the area 4cm in radius around exit point which shows nearly x3 increase in the light collection when SiPM is unprotected compared with essentially no adverse increase in the collected light in the tile with a stopper.

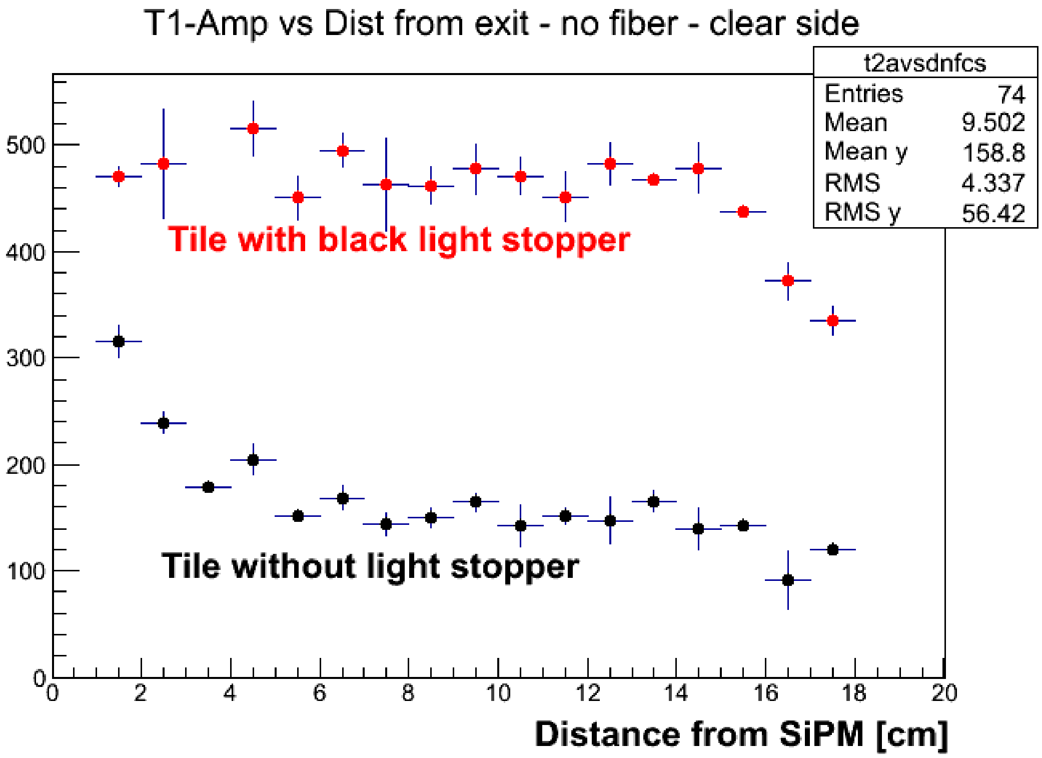


Figure 14: SiPM amplitude dependence on the distance between light injection point and fiber exit point. Black - tile without bulk light stopper, Red - tile with black bulk light stopper.

## 5 Summary

Our results prove that effects of bulk light and cladding light on the uniformity of light collection from large area tiles with embedded fibers could easily be ameliorated with a small modification to tile/fiber design (addition of black bulk light stopper). Unfortunately it is impossible to claim that our data have much of a predictive power for the tile response to ionizing particles. In particular they are not for use in physics simulation. Existing data on the mapping of light collection from large tiles with embedded fibers similar to ours are also somewhat misleading in that sence.

The overview (low position resolution) mapping with cosmic muons usually indicate

20% nonuniformity in the light yield in the range of ±2cm close to the fiber consistent with combined effects of direct light attenuation with attenuation length of a few [cm] and a similar loss in fiber acceptance for direct light. At a longer distances collected light is dominated by diffusely scattered component and stays nearly constant.

The LED exposure with unprotected fiber is even less informative in that sense. In proximity to the fiber the collimated LED light reaches fiber (even through the coating on the clear side of the tile) without rescattering and resabsorption steps making LED testing of the tile light collection nearly meaningless. On the other hand - LED offers an excellent way of testing optical models for light propagation and collection in tiles (including LEDs with peak emission at different wave length).

Certifying these data for simulation can′t be done without additional detailed measurements with cosmic and they are yet to be made.One obvious idea worth be tested immediately: if picture outlined above is correct then painting black over the narrow strip of epoxy above the fiber in the groove can be the cheap and straightforward way to correct the fiber induced nonuniformity in the vicinity of the fiber.