OPTIMIZATION STUDIES FOR A SCINTILLATOR-TILE TO WAVELENGTH-SHIFTER FIBRE LIGHT READOUT FOR THE TESLA-CALICE TILE-HCAL

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Actual R&D results for the optimization of the light signals, response uniformity and granularity of the TESLA Tile-HCAL option as obtained in several institutes of the CALICE collaboration are presented and summarized. Most efforts so far were concentrated on improvements of the light output of the scintillator-tile plus reflector and the wavelength-shifter system (TFS).
The inquiry for appropriate large gain photo-detectors together with the design and optimization of preamplifiers is on the way and will be described in a separate note.
To study possible long term ageing damages of the various considered TFS arrangements a special test device has been built and its sensitivity will be continuously improved to monitor the TFS-ageing at a ~ 1 % level. A MiniCal prototype version with up to 117 photo-detector channels is also used for the study of stability, gain monitoring with LED signals, attainable calibration precision with MIPs and noise contributions.
To demonstrate the performance in hadronic particle flow measurements as predicted from simulation studies a $\sim 1m^3$ Tile-HCAL prototype with 40 layers and about 8000 calorimeter cells is been built.

1. The R&D program

A proposal for a TESLA calorimeter with a Tile-HCAL was submitted to the DESY-PRC in autumn 2000 with additional addenda in May and September 2002 [1]. The collaboration was asked by the PRC to prove the feasibility of such a Tile-HCAL option and to compare it in performance (e.g. jet energy resolution, cluster separation and response stability) with other proposed digital HCAL options. Since then, in a joint effort of the contributing Czech, German and Russian Research Institutes [2] a variety of R&D studies has been carried out:

- selection of best available plastic scintillators: DESY, ITEP, LPI
- studies for production of cheaper scintillators on polystyrene base at Vladimir (ITEP) and at Protvino and Kharkov (LPI)
- appropriate WLS-fibres; DESY, LPI
- tile reflector coating and wrapping; DESY, LPI
- optimal geometry of tile-fibre coupling; DESY, LPI
- TFS light yield optimization measurement and study of response uniformity for small tiles; DESY, ITEP, LPI, Prague
- similar studies for larger tiles; Prague
- simulation studies for TFS optimization; ITEP
- clear fibre coupling and read-out; DESY
- the search for and study of appropriate photodetectors and preamplifiers; DESY-H1, ITEP, MEPHI, Prague
- tests of photodetectors and preamplifiers with MIP's; DESY-H1, ITEP, MEPHI, Prague
- front end electronic concepts; DESY-H1
- simulation studies for optimization of TFS granularity for beam tests; DESY-H1, ITEP
- and design and equipment studies for several prototypes, for TFS ageing studies and beam tests; DESY, LPI, Prague

The tests were made with radioactive sources, cosmic muons and in a DESY electron test beam.

2. The search for the best scintillator

A significant fraction of the detector cost is due to the large quantities of plastic scintillator (with 5 mm thickness) for the tiles. The Tile-HCAL prototype will be equipped with ~ 40 m^2 of such scintillator tiles, the final TESLA calorimeter needs ~ 4000 m^2 to instrument the barrel and end-cap sandwiches. Various samples of 5 mm thick plastic scintillator were used for tests at DESY. Tiles were cut, polished and distributed for tests to the various institutes. With the test beam set-up at DESY using a Multi-Anode-PM (MA-PM) and CAMAC-read-out for the tile-fibre system test many tiles can be studied at same time. We investigated the commercially available scintillators Bicron (BC-404,BC-408,BC-416), Kuraray (SCSN-81) and also new developed scintillators with improved light yield (Kuraray SCSN-62A and -62B). By far the best scintillator found was BC-408, made from polyvinyl-toluol (PVT) with reduced light attenuation, resulting in $\sim 50\%$ more light yield compared to the second best (SCSN-62A).

In order to get cheaper scintillators, inquiries were made to find or produce scintillators in Russia. Contacts were opened to Kharkov (Monocristal-Reactive), Vladimir (Polimersintez) and Protvino (IHEP). Their scintillators were tested and as a consequence in Protvino (via LPI) and Vladimir (via ITEP) better polystyrene based scintillators have been produced and tested at DESY and ITEP, the best of these scintillators, SC-306M from Protvino, exceeded the light yield of the Kuraray SCSN-81. Also, in the Russian factories, studies are underway to optimize casting procedures for large quantities of tiles or larger structured tile plates.

3. Studies of the Tile WLS-fibre system (TFS)

The TFS consists of WLS-fibres inserted in optimal way in scintillator tiles. To optimize the light transfer to the fibres, the tile and the fibre need to be enclosed in efficient reflector material. For the transfer of the wavelength shifted light to the photodetectors in some cases clear fibres with reduced light attenuation have to be connected/glued to the WLS-fibres. Table 1 lists all scintillator-, reflector-, WLS and clear fibre materials and optical glues investigated for the TFS optimizations.

3.1. *Reflectors for the scintillator tile*

To minimize the leakage losses of scintillation light the tiles were coated by reflective painting (TiO_2) or wrapped with reflective foils of Tyvek (with diffuse reflection) or with a new 3M-Reflector ("Radiant Mirror Film", multilayer mirror reflection) with $\sim$ 99% reflectivity in the whole wavelength range of concern between 350 and 700 nm. An alternative methode uses improved surface reflection on the tiles by a special chemical bath treatment ("matting") in the VLADIMIR company in Russsia which produces small reflecting bubbles on the edge surfaces of the scintillators. This method was studied and is used already for the ECAL of LHCB.

3.2. *The WLS-fibres*

The scintillation light emitted in a wavelength range between 350 and 450 nm is absorbed in the attached WLS fibre and isotropically re-emitted with larger wavelength of $\sim$ 500 nm. To protect the fibres mechanically and keep the transformed green light contained in the WLS-fibres, a double clad coating is chosen which has 50% higher light yield with respect to a single clad because of larger trapping efficiency [3].The open fibre end has to be polished carefully and covered with an optimal reflector to contain also the light emitted in the direction away from the photodetectors. Typically 5-7% of the light produced can be contained in the WLS core volume and guided to the photodetectors. To catch most of the scintillation light, WLS-fibres of 1 mm diameter are optimal. WLS fibres of smaller cross-sections catch less direct scintillation light whereas fibres with larger diameters are less flexible for bending to small loops and risk enhanced ageing damages. The following WLS-fibres were tested: larger quantities with many samples from Bicron BC-91A and BC-92, Kuraray Y11 (with 200, 300 and 400 ppm of WLS-additive) and a single sample from Poly High Tech (Italy).

Table 1. Materials studied for tile-fibre-system optimisation.

component	product	comments
plastic scintillator	Bicron BC-404	base-material PS
	Bicron BC-408	base-material PVT
	Bicron BC-416	base-material PS
	Kuraray SCSN-81	
	Kuraray SCSN-62-A	new development
	Kuraray SCSN-62-B	new development
	Protvino SC-306	new development, LPI
	BASF-SC-143	new development, PS, ITEP
tile reflector	Bicron BC-620	reflective paint, base TiO_2
	reflector foil Bicron BC-642	white Teflon
	Al-coated mylar	producer Dupont
	Tyvek paper	white,diffusive
		thicknesses: $50, 75, 100, 150\mu m$
	3-M "Super-Radiant"	super-reflector foil, many selective reflection layers
WLS-fibres	Bicron BC-91A	double clad, 1.0 and 0.8 mm diam.
	Bicron BC-92	1.0 and 0.8 mm diam.
	Kuraray Y-11(M)	1.0 and 0.8 mm diam.,
		σ-type, with 200, 300 or 400 ppm of shifter
	Poly High Tech S2H8/100	1.0 mm diam.
WLS fibre end cover	Al-coated in vacuum oven	Sternwarte Bergedorf
	colloid reflector painting	producer: Dupont, 2 comp.
	reflector painting	producer: Dupont
	polished only	grain sizes: $0.3, 4, 20\mu m$
clear fibres	Bicron BC-98	double clad, 1.0 and 0.8 mm
	Kuraray Clear-PSM	multiclad (mc), 0.8 and 0.6 mm
medium for fibre couplings	Bicron BC-600	optical glue/cement
	Bicron BC-630	optical grease
	Dow Corning Q2-3067	optical grease
	Stycast	2 components

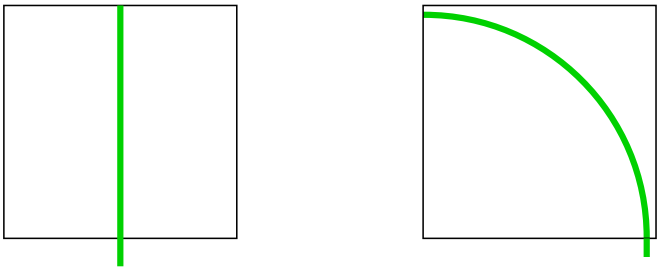
3.3. *The optical scintillator-fibre contact*

Part of the fibre R&D studies could profit significantly from results from previous studies in the CMS collaboration [4]. The light yield of scintillator tiles of

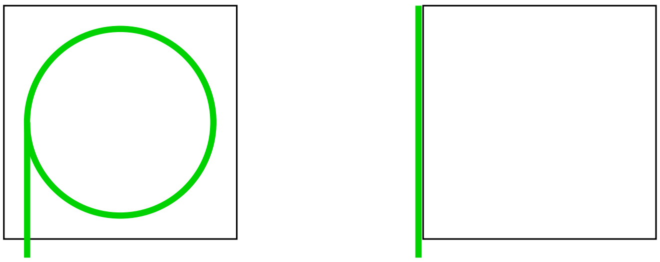
5×5 cm^2 size was measured with WLS fibres attached along one tile side, with optical contact via air gap or optical glue (e.g. Stycast or Bicron BC-600). The coupling of the WLS fibres in appropriate machined grooves (1.1 mm large and 2-3 mm deep) led to improved light yield [5].

3.4. *Geometrical coupling shapes of the WLS-fibres*

The WLS fibres can be arranged in various geometrical shapes, directly attached to the tile surface or inserted in grooves, Fig. 1. The light yield of the TFS improves with increasing WLS-fibre length inside the tiles but was found to saturate, due to absorption of the produced light, when more than 2 WLS-fibre loops were applied.



Center straight fibre **Diagonal curved fibre**



Double looped fibre **Straight fibre on side**

Figure 1. Various geometrical tile-fibre arrangements for the optimisation of light yield.

3.5. *The readout of the light signals*

Small and cheap photodetectors like SiPMs [8] can be directly coupled to the WLS-fibres on the tile. Larger photodetectors have to be mounted outside the active volume and have due to the higher cost to collect the light from several TFS. In such cases, the green light from the WLS fibre has to be guided with minimal losses through a WLS-clear read-out-fibre connection were the fibres are carefully adjusted and glued together with BC-600 optical glue. Typically 80% transparency can be reached. A better method is the coupling of the 1 mm multi-clad (mc) WLS-fibre to a larger, 1.1 mm diameter clear multi-clad fibre where due to reduced adjustment problems less core-light is lost to the cladding of the optical fibre during the transition. Better transmission results for the fibre-fibre coupling were also found when both fibres where thermically fused within a guiding quartz tube. In our tests, up to 90% light transmission was achieved when both fibre ends were polished and the fibre fusing temperature and contact pressure were optimized. Clear double-clad, flexible optical fibres (1 mm diameter) with long attenuation length have to be found to transport the light to the photodetectors outside the calorimeter volume. Fibres to be investigated are Bicron BC-98 and Kuraray "Clear-PSM". The clear and WLS fibres from Kuraray are specially treated (σ-type fibres) to be less sensitive to bending stress at the small bending radii of a few cm. Both fibre types are optimized to have optimal light transport over larger distances, attenuation lengths of $\lambda \geq 8 - 10$ m are quoted by the producers.

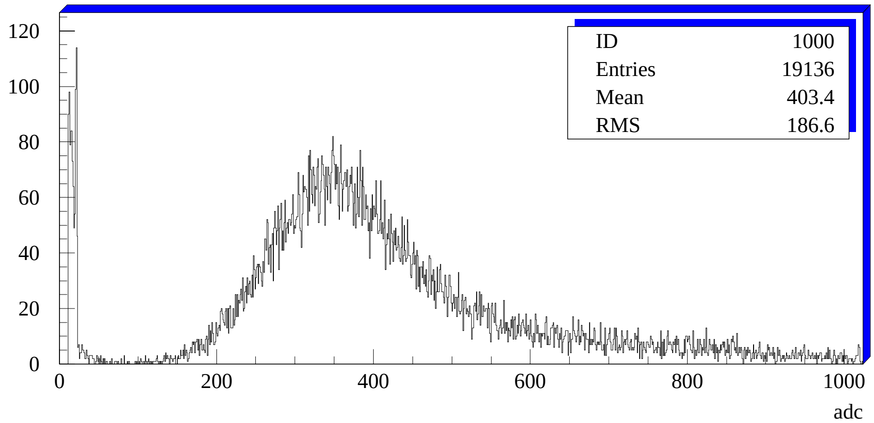
4. The results of the TFS studies

4.1. *Some results from the DESY test-beam measurements*

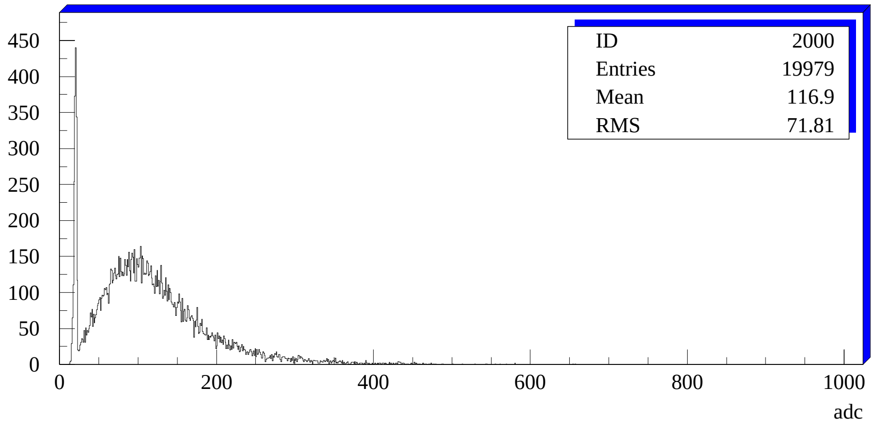
Detailed reports on early R&D results as obtained with cosmic MIP's and Sr^{90}-sources are given in [5,6,7]. Here some new results from DESY/LPI using an electron test-beam at DESY are presented. During the TFS optimization studies a considerable increase of collected light was achieved as demonstrated in Fig. 2. At the early studies with BC-408 as tile scintillator, covered by 2 reflector-layers of Tyvek and straight fibre side read-out by un-mirrored BC-91A WLS fibre, typically 8-9 Ph.e. were obtained. With 3M foil as reflector-layer and a 3M-mirrored Y-11 WLS fibre inserted in a curved diagonal groove up to 25.5 photoelectrons (Ph.e.) could be obtained.

Some of the final results which followed many previous optimization steps during the last 12 month are listed in Table 3, for BC-408 scintillator and Table 4 for the Protvino SC-306 scintillator.

There is a lot to extract from these tables to improve the TFS LY and to narrow the field for the next R&D steps:



BC408, 3M, Y-11 mirrored, curved diagonal groove



SC306M, 2Tyvek, BC91A no mirror, middle groove

Figure 2. Progress in light yield optimization: MIP spectra from the DESY e-beam test, measured with a Hamamatsu H8711-10 PM. From the lower to the upper plot, due to better scintillator, tile-reflector and WLS fibre optimization, as described in the text, the light yield was improved by ~ 3.

—–comparing different WLS-fibres: the LY for Kuraray Y-11 WLS fibres is better than BC-91A by $(26 \pm 2)\%$ with open polished fibre end, for both fibres with Al-coated fibre ends the difference is remarkable smaller: $(12 \pm 1)\%$. For SC-306 tiles read out with un-mirrored fibres the difference in LY between Y-11 and BC-91A is as small as $(8 \pm 1)\%$,

—– fibre end reflector: Al deposit on Y-11 increases the LY, compared to polished fibre end only, the increase is $(18 \pm 4)\%$, in the case of open fibre end the light is reflected outside the fibre on the tile-reflector, this reflection can be made more efficient, when the open end is tightly covered by the tile-reflector

without an air gap. Studies are in preparation to improve this type of reflection for the beside, middle and diagonal coupling.
—– tile-fibre coupling media: BC-600 gluing improves for center groove the measured LY compared to air by $(11 \pm 3)\%$, but no effect is seen for 2-loop WLS read-out, the results fluctuate between $\sim \pm 6\%$. From these measurements one can conclude, that due to the TFS quality, most of the scintillation light survives multiple reflection and absorption and is caught in the 2-loop WLS finally. Than no further improvement can be expected by optimizing the fibre-tile contact;
—– tile reflector: 3M reflector increases the LY compared to Tyvec by $(40 \pm 9)\%$.
These factors are linearly extracted; care has to be taken to apply several of them in an additive way. For example Al-mirroring the open end of a 2-loop fibre is much less efficient, since the light emitted away from the read-out direction is partly absorbed along the long path (2x fibre length) of the tightly bent fibre. Also, if the scintillation light survival path in the TFS is long enough due to low intrinsic absorption and high reflectivity of the tile coating, the fibre coupling strength can be reduced. The LY of the WLS-fibres depends on the scintillation light wavelength spectrum offered by the scintillator. This can be optimized in future when the scintillator material is finally selected.
The light yield from BC-408 is significantly larger than from the best Russian scintillator, the difference depends strongly on the coupling length of the attached WLS-fibre with a measured ratio in LY for:

- center groove read-out: $(95 \pm 5)\%$,
- diagonal curved read-out: $(74 \pm 11)\%$,
- 2-loop read-out: $(31 \pm 4)\%$

This can be explained by stronger light attenuation in polystyrene as compared to polyvinyl-toluol. The measured light yield of SC-306 is $\sim 9\%$ higher as for BASF-143 (Vladimir), nevertheless both Russian producers will use in future “optical clean polystyrene” from Dow Chemical where due to reduced light attenuation a higher light yield ($\sim 30\%$) can be expected.

The results are compared in Fig. 5, 6, 7. The highest yield, namely ~ 25 photoelectrons from the Bialkali photocathode multiplier with $\sim 11\%$ photocathode efficiency at 500 nm (Hamamatsu H8711-10) was achieved with tiles from Bicron BC-408 scintillator ($5 \times 5 \times 0.5$ cm^3) covered with super-reflector foil from 3M and viewed by 1 mm diameter Y11(200) multi-clad WLS fibres. Polishing and cleaning (with soap and distilled water) of the tile surfaces and the reflector and specially the careful fibre open end polishing improved the light yield significantly compared to earlier results [5]. Within the measurement

WLS	Groove's shape	Mirror end	Reflector	Coupling	Light yield (Ph.e)
BC91A	beside	No	2 Tyvek	air	8.79 ± 0.57
BC91A	beside	Yes	2 Tyvek	air	10.2 ± 0.48
Y-11	beside	No	2 Tyvek	air	11.27 ± 0.58
Y-11	beside	Yes	2 Tyvek	air	11.35 ± 0.74
BC91A	beside	No	3M foil	air	11.82 ± 0.96
BC91A	beside	Yes	3M foil	air	15.1 ± 1.0
Y-11	beside	No	3M foil	air	14.6 ± 0.81
Y-11	beside	Yes	3M foil	air	16.88 ± 0.98
Y-11	middle	No	3M foil	air	15.08 ± 0.69
Y-11	middle	No	3M foil	glue BC-600	17.2 ± 1.0
Y-11	middle	Yes	3M foil	air	17.06 ± 2.1
Y-11	curved diagonal	No	3M foil	air	21.56 ± 0.67
Y-11	curved diagonal	No	3M foil	glue BC-600	23.35 ± 1.0
Y-11	curved diagonal	Yes	3M foil	air	25.34 ± 1.26
Y-11	2 loops	No	3M foil	air	21.51 ± 0.89
Y-11	2 loops	Yes	3M foil	air	25.26 ± 0.66
Y-11	2 loops	No	3M foil	glue BC-600	22.86 ± 1.0
Y-11	2 loops	Yes	3M foil	glue BC-600	23.63 ± 1.0

Figure 3. Table 2, TFS light yield measurements with the DESY test-beam. The tile scintillator is BC-408 (Bicron). Studied are the influences of different WLS-fibres, different geometrical fibre coupling shapes and coupling media, the fibre end mirroring or polishing and the 2 best tile reflectors.

WLS	Mirror end	Groove's shape	Reflector	Coupling	Light yield (Ph.e)
BC91A	No	middle	3M foil	air	7.06 ± 0.3
BC91A	Yes	middle	3M foil	air	8.42 ± 0.26
Y-11	No	middle	3M foil	air	7.59 ± 0.35
Y-11	Yes	middle	3M foil	air	9.0 ± 0.64
Y-11	No	curved diagonal	3M foil	air	13.3 ± 1.4
Y-11	Yes	curved diagonal	3M foil	air	13.7 ± 0.54
Y-11	No	2 loops	3M foil	air	16.2 ± 1.4
Y-11	Yes	2 loops	3M foil	air	18.77 ± 0.7
Y-11	No	2 loops	3M foil	glue BC-600	18.7 ± 1.0
Y-11	Yes	2 loops	3M foil	glue BC-600	17.79 ± 1.0

Figure 4. Table 3, TFS light yield measurements with the DESY test-beam. The tile scintillator is SC-306 (Protvino), the reflector used is 3M Super-Reflector. Studied are the influences of different WLS-fibres, different geometrical fibre coupling shapes and coupling media, and fibre end mirroring or polishing.

errors 2-loop and curved diagonal WLS-fibre coupling showed same yield. The improvement to WLS side read-out (with air coupling) was 1.5 (for 3M reflector) and 2,2 (for Tyvek reflector).
In addition the response of many TFS of same configurations can now be equalized to better than $\sim \pm 4\%$.

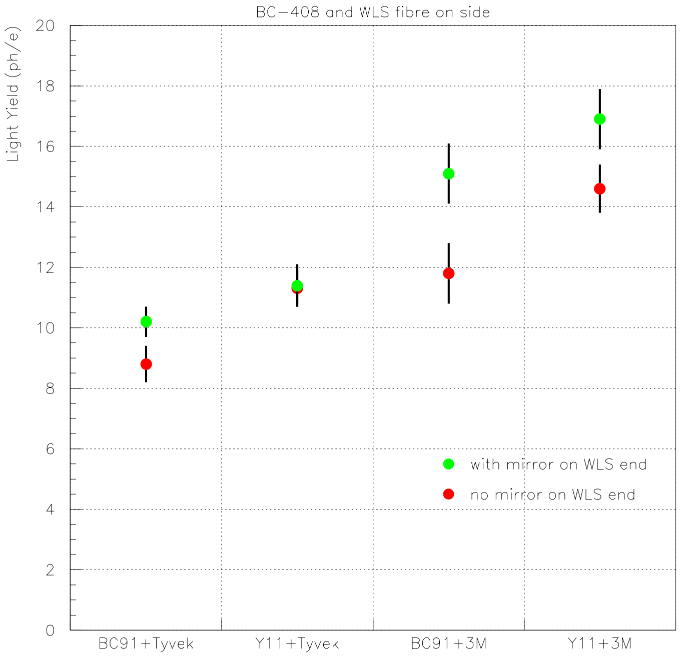


Figure 5. Measured light yield for the TFS with 2 different WLS fibres, 2 different tile reflectors and 2 different fibre end treatments. The scintillator studied here is BC-408. The tile is read out by a straight fibre along tile side. Significant increase in light yield is observed, when best WLS fibre and reflector material is used.

The spread in lateral uniformity for the best configurations is smaller than $\sigma = \pm 3 - 4\%$. The TFS made from Protvino SC-306 are within these limits (see Fig. 8a,b) better uniformity was found for BC-408 with middle or diagonal groove read-out, as demonstrated in Fig. 8c. WLS loops with $r = 2.4$ cm embedded in 2-3 mm deep tile grooves give rather good light yield, 2 loops catch more light than 1 loop alone, but for 3 loops no significant additional light yield is observed. Thus the latest loop optimization studies and comparisons with other configurations were made with a 2-loops fibre read-out.

For such strong bent fibres long time stability and ageing studies have been started with a special device based on pulsed UV-LED flashes sent to scintillator tiles. The scintillation photons produced by the LED-light are transmitted to the inserted WLS-fibres, converted to green light and the caught fraction is - via various test-loops - conducted to a common photodetector. Up to 5 WLS-loop systems can be studied in sequence. An additional straight WLS-fibre read out is used for reference. The precision aimed for these measurements is on the level of ±0.5%, at present we reach ±1.5%.

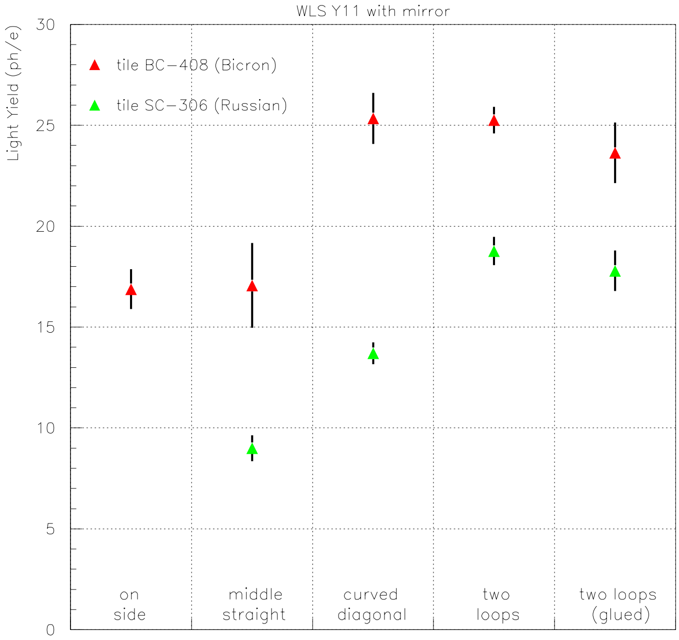


Figure 6. Measured light yield for TFS with Y-11 WLS fibre read-out. The scintillators BC-408 and SC-306 are compared for different TFS configurations.

Individual TFS systems of same size and fibre configuration have to be added to cells (3-7 tiles in the actual concept), thus their light yield has to be equal within a few percent. Fluctuations of $\sim \pm 4\%$ were observed for the small TFS samples as mentioned above. This is sufficient to avoid deterioration of achievable energy resolution. In any case, it is possible to reduce the light yield of individual tiles by insertion of a small dimming strip (black paper, 0.5 mm wide) along the center of the tiles. The LY reduction is $\sim 0.85\%$/mm as demonstrated in Fig. 9. The response uniformity - with 1 cm dimming insert - is still better than $\pm 3\%$, Fig. 8d.
As it can be deduced from Fig. 2, the configuration options for the best LY are “curved diagonal” and ”2-loop” couplings. The “curved diagonal”option needs less WLS fibre material, has no strong bending, thus less ageing risk and a fibre open-end reflector can be applied after fibre in tile insertion and gluing. In addition the fibre end fine polishing can be made finally before the TFS is coated with reflector. All this leads to an easy manufactoring procedure for this option.

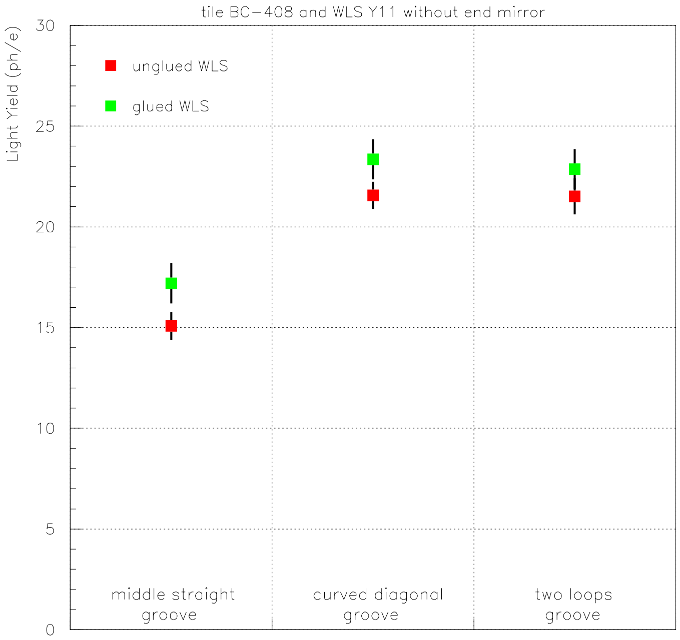


Figure 7. Measured light yield for some TFS configurations with optical contact between tile and fibre by air or glue (BC-600). Scintillator is BC-408, WLS-fibre is Y11(200)M.

4.2. *Some results from the ITEP group*

The ITEP group has constructed two TFS test equipments with fibre read-out to a 12 stage Hamamatsu R329-02 photomultiplier ($\sim$ 10% mean quantum efficiency):
— A x-y scanner set-up with a β - source to study the response uniformity across the tiles and to compare the relative LY of the various TFS arrangements. This device has a position precision in x,y of $\sim$ 1 mm (2 mm collimator) and a precision in signal amplitude measurement of $\sim 1-2\%$.
—A test-trigger telescope for MIP from cosmic muons or penetrating electrons from a β - source. With the help of an appropriate LED calibration this set-up can be used to measure the absolute TFS-LY for MIP's in number of photo-electrons.
A lot of measurements were carried out, mainly for TFS with BASF-143 based casted tiles from Vladimir. Tile sizes of $5\times5, 7\times7, 9\times9$ and 16×16 cm^2 were studied with single and 2-loop read-out. WLS-fibre was Y-11, the fibre end reflector was made by a chemical treatment called “mating”, which produces micro-bubbles of the base material on the fibre end surface. The total length of WLS fibre between tile and PM was always 110 cm, compared to $\sim$ 60 cm

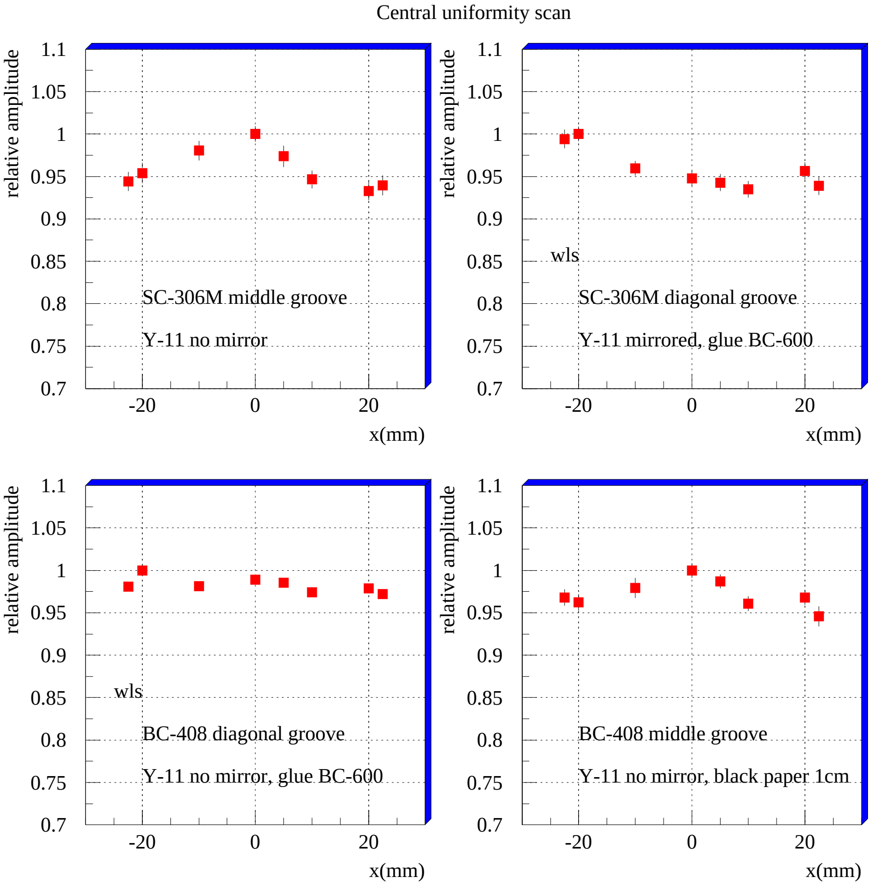


Figure 8. Various different TFS, elcectronescanning across tiles to find the best configuration for uniformity.

at DESY. It was found that insertion of a 2 fibre loop increases the LY by ∼ 45% with respect to 1 loop only.

Recently ITEP got a new reference TFS (definition: 5×5 cm^2, BC-408, 3M-reflector, 60 cm of Y-11 WLS, 2-loops, glued fibre, without end mirror) and measured it in their set-up to compare the results. They found ∼ 20.5 Ph.e. (23.6 Ph.e. were measured at DESY) which is in good agreement when the measurement errors and photodetector light-coupling problems are taken into account. This is about 1.35 more light than seen from an ITEP-made TFS (BC-408, 3M, 2 loops, Al coated fiber end, unglued fibre) if the fibre read-out is reduced to the same fiber length between tile and PM according to the light attenuation measured at ITEP shown in Fig. 10.

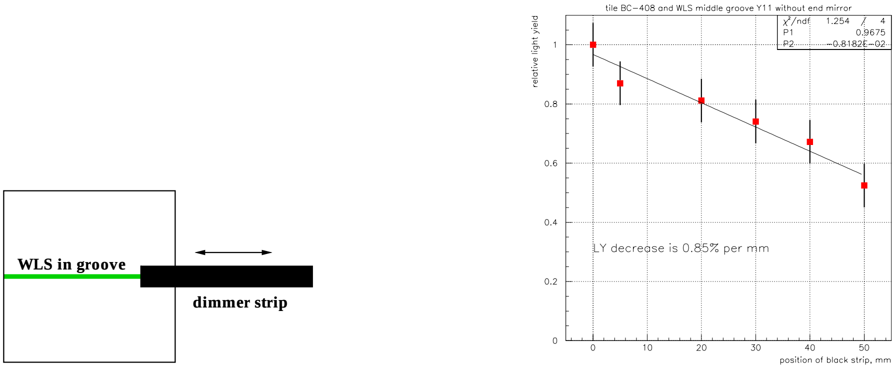


Figure 9. Method and result of dimming of the light output of individual tiles.

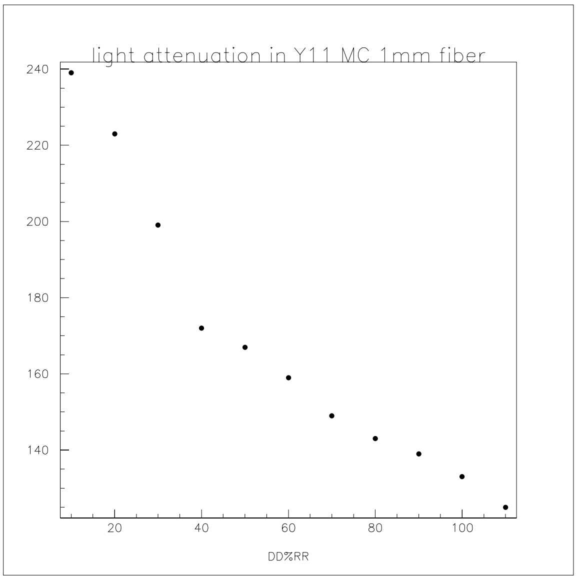


Figure 10. The measured light attenuation in Y-11 (Kuraray).

The difference observed in both measurements is assumed to be due to the proper tile-reflector cleaning for the reference tile and the glue-coupling of the DESY TFS. ITEP finds a significant increase in LY for glue-coupling of $\sim$ 1.35 for 2-loops and at least 1.7 for a center straight groove. Such strong LY

increase can be understood when reflection- or attenuation losses occur along the scattered light-path in the tile and reduce the amount of scintillation light which finally enters the WLS fibre. Then an early, effective light transfer to the fibre - due to the better glue-coupling - becomes more important. For the high yield TFS as measured at DESY the gluing improvement for 2-loops was found to be small within the errors.
The influence of fiber end mirroring is large, a gain of order 1.5 is observed with aluminized fiber end, compared to a "matted" fibre end, for 2-loop read-out. At DESY a much smaller effect is observed.

Table 2. LY from TFS for the 4 different plastic scintillator materials and various TFS geometrical WLS-fibre configurations. More details are given in the text.

Tile size,cm	SCSN-81	Vladimir,BASF-SC-143	Protvino,SC-306	BC-408
1 WLS-fibre loop, non glued				
5 x 5	8.4	11.1	11.5	18.8
9 x 9	8.4	11.0	11.0	19.1
16 x 16	7.2	6.9	7.4	
2 WLS-loops, glued				
5 x 5	13	17.2	17.8	29.1
9 x 9	13	17.1	17.1	29.6
16 x 16	11.2	10.7	11.5	
diagonal WLS-fibre, glued				
5 x 5		13.	13.5	22.
fibre along tile side, glued				
5 x 5		8.	8.3	16.9

In the table 2 different TFS tile sizes with various geometrical fibre configurations are compared for all scintillators available. The TFS parameters were: 3M-SR reflectors, Y-11 WLS-fibres, Al-covered fibre end, The LY is given in number of Ph.e./MIP/tile detected in the R329-02 PM for
– 1 loop read-out (first 3 lines), air contact between tile and fibre
– 2 loop read-out (next 3 lines), fibre glued to tile, BC-600
– diagonal fibre read-out, fibre glued to tile, BC-600 and
– fibre along tile side, fibre glued to tile, BC-600.
The best tile-scintillator is confirmed to be BC-408. To note, that the best ITEP LY for the 2-loop read-out of a 5×5 cm^2 BC-408 tile is larger than the LY they measure with the reference tile delivered from DESY (29.1 Ph.e. compared to 20.5 p.e. as mentioned above). More investigations are required to understand such a difference. SC-306 is $\sim$ 5% better than the Vladimir tile. The yield of both is about 60% of BC-408. Large BC-408 tiles were not available at that time. One can conclude from these measurements that for the Russian scintillator tiles a 2-loop read-out is needed to get enough LY.

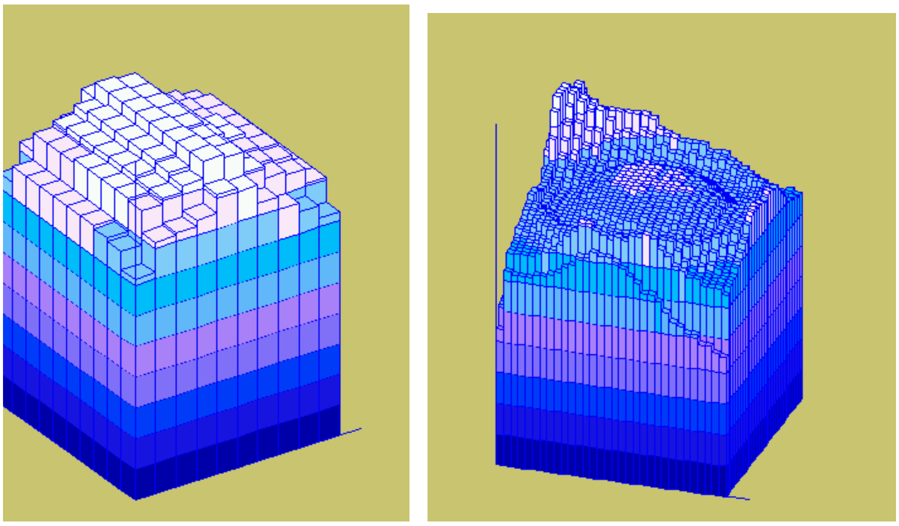


Figure 11. Uniformity scan at ITEP, scintillator tiles from Vladimir, Tyvek reflector, measurement in 5 mm steps in x and y, a) 5×5 cm^2, center straight b) 16×16 cm^2, 2-loop fibre read-out.

Some results from the uniformity measurements are shown in the Fig. 11. The left plot shows the uniformity scan as measured for a 5×5 cm^2 tile with air coupled center fibre read-out. The non-uniformity observed is significant, due to the tile material and reflector used. In second figure presents the uniformity scan of a large tile (16×16 cm^2) is presented. Again, the non-uniformities seen at the 4 corners are due to the materials used. For large size tiles clearly BC-408 scintillator and 3M-SR reflector have to be used.

Satisfying global agreement was found between the groups, the best TFS yield was confirmed. But not all results of the different institutes are, when carefully compared, properly understood so far. This is stimulating. Some measurements have to be repeated for the final TFS optimisation.

4.3. *Some R&D results from the Prague group*

The TFS studies were made in spring and summer 2002, at a time where not all best material components were available for tests. Also the polished WLS-fibres had no end mirror. Nevertheless a lot of information can be extracted from these measurements on the way to the final component optimisation.

The measurements were made with a Sr^{90}-source of 1.5 MBq. The LY was measured with a PM (R5505, Hamamatsu) and an pico-electrometer (Keithley 6514). The x-y scan resolution is 5 mm. A test-trigger telescope for MIP's from cosmic muons and alternatively a β - source allow to study the response of MIP's and - with appropriate LED-calibration - to measure the absolute number of photoelectrons. Table 3 lists some results for different WLS fibres, fibre diameters, optical coupling media and - geometry, and tile reflectors. The scintillator tiles used are BC-408, 5 × 5 cm^2. The best LY was obtained with Tyvek reflector and 2 WLS loops. With the improvement factors discussed in the previous chapter for 3M-SR reflector and Y-11 WLS-fibre, end mirrored, more than 25 Ph.e. are expected for one tile. Some more conclusions to draw from these measurements:

Table 3. Results from TFS optimisation studies in Prague.

WLS	(mm)	Groove	Mirror	Reflector	Coupling	LY Ph.e.)
BC-91A	1	no	no	1 Tyvek	air	9.6 ± 0.5
BC-91A	0.8	no	no	3M-SR	air	7.7 ± 0.6
Y11	1	no	no	3M-French	air	15.3
Y11	0.8	no	no	3M-French	air	11.3 ± 1.2
Y11	0.8	center	no	1 Tyvek	glue, BC-600	10.4 ± 1.4
Y11	0.8	center	no	3M-French	glue, BC-600	12.9 ± 1.6
Y11	1	2 loops	no	1 Tyvek	air	16.1 ± 0.3
Y11	1	2 loops	no	1 Tyvek	glue, BC-600	14.9 ± 2.8

- 0.8 mm diameter Y-11 WLS fibres give ∼ 35% less LY for straight side fibre read-out
- 3M super-reflector is 1.24 times better than Tyvek for a straight center groove read-out
- air or glue coupling show no essential difference for 2-loop readout

The uniformity of TFS was studied for straight along side and center tile WLS-fibres and 2-loops.

Fig. 12 shows uniformity measurement scan across a 5 × 5 cm^2 tile (SCSN-81, Kuraray) with 2 WLS-fibre loops (BC-91A, diameter=0.8 mm, mc). Tile reflector is Tyvek. A few percent of decrease in the signal can be observed along the loop shape, together with a small asymmetry towards the fibre read-out direction. Due to the fact that at the early time of R&D studies neither the best scintillator nor the best reflector was used the LY and uniformity results are slightly worse as compared to the recent measurements at DESY.
Also LY and response uniformity to crossing MIP's were studied for 3 relevant tile sizes of $5 \times 5, 10 \times 10, 15 \times 15$ cm^2, with Y11-fibre (diameter=0.8 mm, mc) side read-out, un-mirrored fibre end, for BC-408 covered with Tyvek reflector.

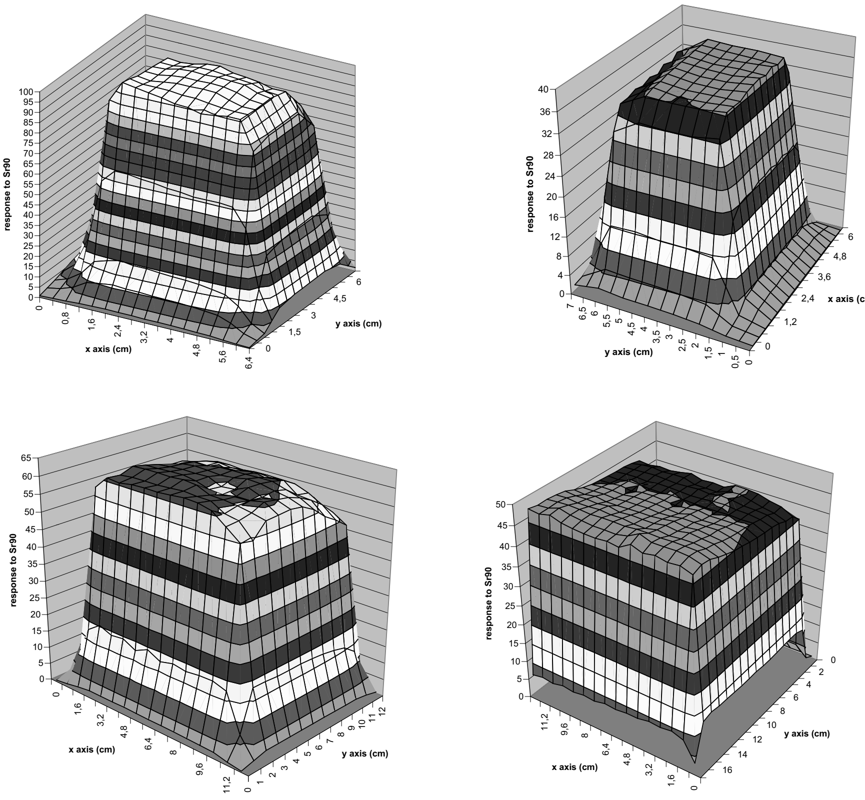


Figure 12. Uniformity scan as measured in Prague: BC-408, Tyvek, Y-11, 1. row: 5x5 cm^2, WLS fibre loop and side read- 1 out, 2. row: 10x10 cm^2, WLS fibre loop, 16x16 cm^2 WLS side read-out.

The results are listed in Table 4. The dominant feature observed is the strong decrease of LY with increasing tile size. This is mainly due to the use of Tyvek. For a 3M-reflector much better results are expected. The use of fibre loop read-out for the larger tiles will increase the LY and also the response uniformity.

Table 4. Various tile sizes, LY and uniformity studies.

Tile a x a(cm^2)	5x5	10x10	15x15
Photo e^-	6.5 ± 0.4	4.0 ± 0.2	2.5 ± 0.2
Relative LY	2.4 ± 0.4	1.5 ± 0.3	1
Uniformity (%)	4.0-6.0	5.0-6.5	4.0-5.5

5. The future R&D program

5.1. *The MiniCal test array*

A small calorimeter test stack with a volume of 21 × 21 × 72 cm^3 has been built with 27 absorber layers (2 cm stainless steel each) where a larger number of individual tiles of various size (up to 165 tiles or 55 cells with 3 tiles each) or large machined tile-plates can be assembled in between and continuously tested by cosmic muons and electromagnetic showers from a test beam at DESY. Such a structure, called MiniCal test-array, is shown in Fig. 13. From the scintillation tiles the WLS fibres will be guided to photodetectors nearby. To read out 64 channels, at the beginning 4 HAMAMATSU multi-anode PM's, with 4x4 anode pads of 4 × 4 mm^2 each, will be used.

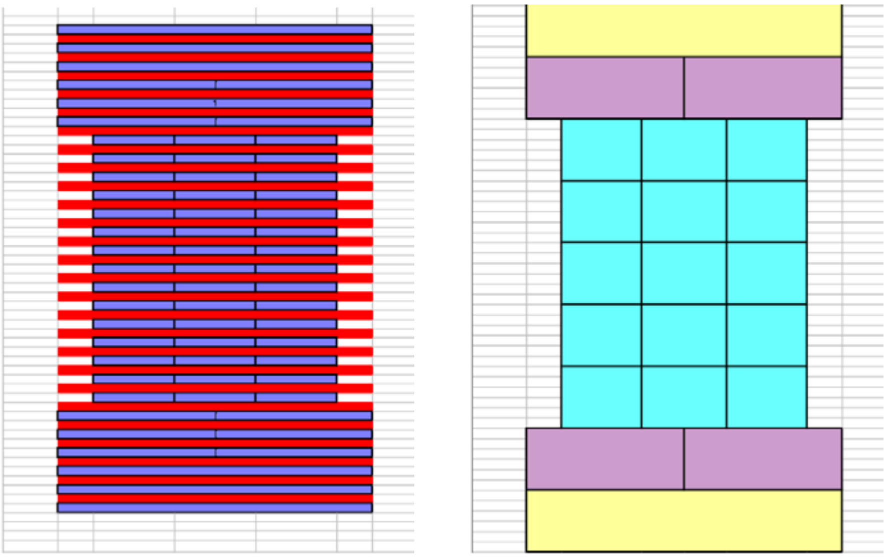


Figure 13. The layer and cell structure of the MiniCal test array.

Other photodetector options as APD's (HAMAMATSU, types S5345-SPL and S5344-SPL (3 × 3 mm^2 sensitive area) and SiPM's from MEPHI/Pulsar (1 mm^2 size, with 512, later 1024 pixels), [8]) will be studied soon.

The low rate of useful cosmic muons, with ~ 0.2 Hz for a 5 × 5 cm^2 tile, requires continuous data taking with the MiniCal at least for a few months. The shower measurements in the electron test beam probe the linearity over the required dynamic range, the cross talk between tiles and cells and also the energy resolution attainable. Later measurements are foreseen to study

- the change in response of the TFS in strong magnetic fields (in up to 4Tesla) and
- the field-induced blow up of the shower volumes (in up to 1.2Tesla).

In order to test the performance predicted by simulation for the shower identification and cluster separation, and to study the realistic calorimeter cluster pattern, a large sample of measured HCAL clusters is needed for the wide range of hadron energies and angles concerned. This requires the construction of a prototype with many calorimeter cells. Such a prototype needs for satisfying containment an active sandwich volume of about 1 m^3 and will be instrumented with tiles of the selected plastic scintillators and WLS fibres, the favored photodetectors, pre-amplifiers, analog/digital conversion and serial DAQ readout.

Simulation and reconstruction studies are under way to find the optimal sizes and minimum numbers of tiles to be inserted and the required accuracy of leakage measurements which finally defines the detector type needed for the tail catcher. Preliminary simulation results suggest a need of about 8000 active tiles of sizes of 3×3, 6×6 and 12×12 cm^2. Such a prototype stack, able to accept the insertion of analog Tile- and/or Digital-HCAL detector layers, will be tested with the ECAL in front. In addition a leakage detector with about 10 attenuation length in depth is required.

6. Concluding remarks

The concept of the TESLA Tile-HCAL calorimeter is based on the realization of a dense arrangement of fine granular cells with WLS- (and possible longer distance clear fibre read out) to sensitive photodetectors which are insensitive to strong magnetic fields. Present R&D studies prove that the number of photons/MIP read out from the calorimeter cells will be ~ 200. Thus avalanche photodiodes with large photocathode efficiency ($\sim 80\%$) but low intrinsic gain of $\sim 100 - 200$, could be used in combination with sensitive charge preamplifiers with low noise level. The large number of photoelectrons also allows good statistical precision for online calibration with muons from cosmic rays. Nevertheless, the properties of the new Geiger-mode SiPM's are very promising and their possible use in large tile calorimeters is being investigated.

A small MiniCal prototype with up to 128 channels is in use and ready for continuous performance, calibration and gain-monitoring studies and a set-up for TFS ageing precision measurements is in operation.

A larger Tile-HCAL prototype with ~ 8000 cells containing hadronic showers almost in the full linear collider jet energy range is required to proof the par-

ticle flow reconstruction concept.
The worldwide effort of the CALICE collaboration will focus in the next few years on the selection and preparation of the hardware and software components and the simulation and reconstruction studies for all proposed prototypes.

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   Czech Institutes:
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   —-Joint Institute for Nuclear research, Dubna
   —-Lebedev Physics Institute, LPI, Moscow
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