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Light Yield from a Scintillator Tile with Embedded Readout Fibers

H. Trost, J. Tonnison, V. Barnes

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Light yield from a scintillator tile with embedded readout fibers*

HANS-JOCHEN TROST

High Energy Physics Division - 362 -
Argonne National Laboratory
9700 S. Cass Ave., Argonne, IL 60439-4815, USA

and

JAMES I. TONNISON AND VIRGIL E. BARNES

Department of Physics, Purdue University,
West Lafayette, IN 47907, USA

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ABSTRACT

We have studied the light yield in two straight fibers embedded in a square scintillator tile by means of computer simulation. The tile and fiber dimensions are taken in the ballpark of interest for the SDC main calorimeter. A fairly flat total response across the tile can be obtained. Important parameters to be controlled are identified.

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1. Introduction

One of the two technological options for the main calorimeter of the SDC detector[1] is a scintillator sandwich calorimeter using lead and iron as absorbers. The scintillator material is structured as approximately square tiles forming towers of about $11 \cdot 11\ cm^2$ size at the inside of the calorimeter. The light generated in the tiles will be read out using wave-length shifting optical fibers. The rate of light transfer and output and the homogeneity of the net response across the tile area are determined by the geometry of the fiber routing and optical and wave-length shifting properties of the tile, fiber and cladding materials. We use a program written by one of us (J.I.T.)[2] for studying this class of problems for straight fibers embedded axis-parallel in rectangular scintillator tiles and run it for a number of configurations approximating options considered for the SDC calorimeter. The settings for material parameters like refractive indices and attenuation length were chosen following advice from J.Proudfoot.[3] The present calculations do not attempt to estimate the number of photoelectrons at the phototube per minimum ionizing particle, only the yield of green photons in a readout fiber per UV photon generated in the tile, for various configurations.

2. Analysis

The model tile for the present purpose has a square shape of size $11 \cdot 11\ cm^2$, containing two straight fibers parallel to one of the axes in mirror-symmetric arrangement. In a first, exploratory round of calculations, we consider two tile thicknesses, 2.5 mm and 5 mm, two fiber diameters, 1 mm and 0.6 mm, and three positions, one at one surface 2.5 cm away from the edge, the second at half height inside the tile also 2.5 cm away from the edge, and the third at half height right at the side of the tile. (Not all combinations for the thicker tiles nor the thinner fibers are simulated.) The following material parameters are used:

	scintillator	*wave shifter*	*cladding*	*wall*
refractive index	1.59	1.59	1.49	1.0
bulk attentuation length	2000 mm	2000 mm		
light conversion length	0.5 mm	0.5mm		

The "light conversion length" refers to the absorption of UV light in the scintillator and blue light in the wave shifter and its re-emission as blue and green light respectively. The bulk attenuation lengths then effectively refer to the propagation of the blue light in the tile and green light in the fiber. The reflection efficiency and uniform reflection probability of the tile walls are set to 0.999. Reflections at the interfaces between fiber core, cladding, tile and air are performed using the average of the Fresnel coefficients for the two possible polarization components. The reflectivity of the wrapping material outside the tile may be either specular or diffuse; in the latter case reflected light is assumed to be isotropic over one hemisphere. An air gap is always assumed between the tile and the wrapping. For most of our calculations, we are neglecting the "light-trapping" effect, *i.e.* we assume that once a green photon is created inside the fiber it will never be lost out of it except by absorption. In reality, the reflection conditions at the fiber surface determine if light is actually caught and transmitted to the photodetector. The trapping of photons leads essentially to a reduction of the absolute light yield but does not affect the relative comparison of configurations nor the uniformity predictions. We will address this particular aspect further below. The propagation of photons from the tile through the cladding into the fiber, including the reflections at both sides of the cladding, is always handled appropriately in the limit of a vanishingly thin cladding. An example for a photon traced through a 5 mm thick tile with 1 mm diameter fibers at one surface is shown in Fig.1. The light yield is effectively determined by the number of green photons travelling in the fiber to the edge of the tile.

UV photons are generated at random height through the thickness of the tile and within a 1 mm radius around fixed points in the area of the tile and then

propagated observing the before-mentioned conditions. For each configuration used, two runs are made:

1. At the center of the tile, 50000 photons are produced to obtain the light yield as a function of the number of bounces the photons made and, separately, of the position where they are collected by one of the fibers, and to measure the distribution of total distance traveled by the photons until observation (Fig.2).

2. On the center axis of the tile at right angles to the fibers, points are chosen starting from $y = 2.5\ mm$ into the tile and every 5 mm thereafter to generate 1000 photons each in order to map the uniformity of the light yield along that axis of the tile (Fig.3).

The figures show that in the configurations chosen, the position of the fibers does not have a large influence on the light yield. Also, the uniformity on the central axis of the tile is not much affected. This is likely caused by the quite ideal optical properties assumed. The yield changes noticeably with the diameter of the fibers, the variation not being linear. Again the ideal optics allow to partially compensate for that difference by still collecting light after long path lengths. Increasing the tile thickness has a very similar effect. Thus the really important quantity here seems to be the ratio of the fiber diameter to the tile thickness, at least as long as the tile thickness is much smaller than the other two orthogonal dimensions in the configuration.

After these exploratory calculations have shown a reasonable performance of the program, we proceed to perform more extensive calculations with higher statistics (five times as many scan points, *i.e.* every millimeter, and 20000 UV photons generated at each point) and address a wider variety of design parameters for single tiles. These include: slanted edges of the tile to accommodate the tower shape in the calorimeter (Fig.4; this would allow the bulk head plates separating and supporting towers to be made flat), reflectivity of the wrapping, the bulk attenuation length of the tile material, the refractive index of the fiber cladding,

the number of fibers, and the reflection quality of the tile surface. The basic tile dimensions are kept as above ($11 \cdot 11 \cdot 0.25\ cm^3$, fiber diameter 1 mm) unless noted otherwise. For slanted edges, the case of a 30° slant, *i.e.* $\phi_1 = 150°$ and $\phi_2 = 30°$ as shown in Fig.5, will be contrasted with rectangular tiles ($\phi_1 = \phi_2 = 90°$). The base area of the tile is kept fixed, thus having the slanted edges possibly hanging over the 11 cm side length of the base.

We begin the discussion by looking at the light yield across the tile for varying reflectivity of the wrapping and the slanted-edges option (Figs.6,7). To understand some trivial modulations in these curves, and all following light yield curves, we note that the UV photons are always generated spread out over the *full* height of the tile. Therefore we will see dips at the locations of the fibers as the fibers themselves cannot create or shift UV light, and we see a fall-off of light yield across the slanted edges in proportion to the actual vertical thickness of tile material relative to the central maximum thickness. Also, the drop in the outermost bins for the rectangular tiles is due to a small part of the cylinder within which the program generates UV photons reaching outside the edge of the tile (the cylinder radius is 1 mm with the first center point located only 0.5 mm into the tile). The reflectivity of the wrapping is set to ideal reflecting (0.999), a conservative value for polished aluminium (0.8), and ideal absorbing black (0.0). The wrapping is taken to cover all sides unlike currently being done *e.g.* by the CDF collaboration in their plug calorimeter upgrade.[4] The response of the tile-fiber system is fairly flat across the tile in the ideal case, and the slanted edges do not produce any change. With decreasing reflectivity of the wrapping, an appreciable amount of light is lost quickly, and the variation across the tile fills a band of about 10% relative width (*i.e.* referring to the mean yield across the tile). All these structures are observable only on the basis of high statistics as demonstated by a rerun of the case of an aluminium wrapped rectangular tile (Fig.8; note also similar fluctuations in Fig.3).

While the step from ideal to 0.8 reflectivity cuts the light yield by over 30%, the distances traveled by the photons in the tile remain fairly long as shown by the

comparison of figures 2c and 9. Consequentially, if we vary the bulk attenuation length of the tile material from our standard value of 2 m down to 25 cm, we obtain a further serious degradation of the light yield (Fig.10), by a factor of about 0.6 for the extreme case. Thus, the attenuation length should be *much* larger than the side length of the tile. Some light may be recovered by increasing the fiber diameter (Fig.11) as we have seen earlier already in the low statistics calculation (Fig.3; that assumed ideal reflecting wrapping). Note that the dips due to the readout fibers do not scale with the overall level because there is no scan point coinciding with the center of a fiber, and the fiber diameters we are looking at are of the order of both the scan step size and the photon source size used. In these cases, we have kept the light conversion length in the fiber (for the wave shifting from blue to green) at half the fiber diameter to roughly keep the collection efficiency of the fiber independent of the radius. Thus we observe an effect purely due to the geometric dimension of the fiber. Going to a smaller fiber diameter and trying to rescue the signal by doubling their number has only incomplete success (Fig.12). Accordingly, the choice of fewer but thicker fibers is the better way to go, giving the added advantage of having to handle fewer fibers outside the calorimeter cells.

Next we address the light trapping inside the fiber (Fig.13). We still count the photons essentially just outside the tile for determining the yield but now only those photons trapped by total internal reflection - a small fraction of the green photons generated (see Figs.6 and 13). The governing factor for trapping light inside the fiber is the difference between the refractive indices of the fiber (taken the same as for the tile) and the cladding. If the difference increases, less light will make it from the tile into the fiber in the first place, but once it is in, its chances to stay there are greatly improved. Light is considered terminally lost out of the fiber, if it leaves the cladding to the outside. A larger difference between the refractive indices of the fiber core and cladding the more efficient choice (Fig.13) for collecting light inside the fibers. However, in a realistic system like *e.g.* the one envisaged for the SDC detector,[1] the increase of light collection

is less profitable than it seems: It appears only because the critical angle for total reflection changes, allowing photons to remain in the fiber at large angles with respect to the fiber surface. This larger angle translates into a longer effective path length along the readout fiber to the photon detector. If as in the SDC case the fiber itself is already very long, even optimistic absorption lengths of some 2 m will prevent much of the gained light from reaching the photon detector.

A final effect we have looked at is to have diffuse reflections instead of specular reflections by the tile wrapping. As a model, we assume here that a reflected photon may go anywhere with equal probability on the same side of the wrapping as the incident photon. Superimposing this effect on the previous case does not give any noticeable change in the result (Fig.14). This may change if the bulk attenuation length of the tile is significantly shorter than the 2 m that we have assumed. The relative comparison between the rectangular tile and the slanted tile (Fig.15) remains unchanged by the added effects of trapping and diffuse reflection.

3. Conclusions

We have studied the dependence of the light yield from a scintillator tile read out by fibers on a number of properties of the material involved. Important parameters to pay attention to include the following:

1. The bulk attenuation length of the tile has to be much larger than the tile dimensions. Values of the same size as needed for the long, clear readout fibers are a reasonable choice.
2. The reflectivity of the wrapping should be as high as possible.

Once these conditions are satisfied, the use of slanted edges, even as much as 30°, reduces the light yield by a factor of no more than 0.8.

ACKNOWLEDGEMENTS

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REFERENCES

1) Solenoid Detector Collaboration, G.H.Trilling et al., SDC-90-00085 and SSC-EOI-3, SSC Laboratory, Dallas, Texas, May 24, 1990, and SDC-90-00151 and SSC-LOI-1, SSC Laboratory, Dallas, Texas, November 30, 1990

2) Program BOX, version 15, J.I.Tonnison, Purdue University (mailing address: FNAL, MS 223, P.O.Box 500, Batavia, IL 60510), 1990, and version 17, 1991 (unpublished)

3) J.Proudfoot, Argonne National Laboratory, private communication

4) J.Freeman and P.Limon, Fermi National Accelerator Laboratory, private communication

FIGURE CAPTIONS

1. Projections of a $11 \cdot 11 \cdot 0.5\ cm^3$ tile with 1 mm diameter fibers at one surface, with a photon trace drawn in; the photon originates near the center of the tile.

2. Light yield over number of bounces (top), number of photons over total distance traveled (middle), and contribution to light yield in dependence on point of incidence into the fibers (bottom), for various configurations (see text) of fiber diameter and position and tile thickness:
   a) 1 mm fiber inside 2.5 mm tile,
   b) 1 mm fiber at side of 2.5 mm tile,
   c) 1 mm fiber at top surface of 2.5 mm tile,
   d) 0.6 mm fiber at top surface of 2.5 mm tile,
   e) 1 mm fiber inside 5 mm tile,
   f) 1 mm fiber at top surface of 5 mm tile.

3. Light yield over position along center axis of tile across the fibers, for configurations as in Fig.2.

4. Cut view along the beam axis of the calorimeter in the design used in the SDC LoI[2]

5. Side view and coordinate definition for slanted tiles

6. Light yield dependence on the reflectivity of the wrapping for a rectangular tile

7. Light yield dependence on the reflectivity of the wrapping for a 30° slanted tile

8. Light yield for rectangular tile with reflectivity of 0.8 of the wrapping, mapped with only 500 UV photons per scan point

9. Distance traveled by blue photons in a rectangular tile with reflectivity 0.8 of the wrapping for a production point 1 mm away from the edge, centrally along the fiber direction

10. Change of light yield with bulk attenuation length of tile for blue light, for reflectivity of 0.8 of wrapping

11. Change of light yield with fiber diameter, for a rectangular tile with reflectivity of 0.8 of the wrapping

12. Light yield from four fibers in two arrangements (all at the surface on one side (solid line), alternating using both sides (dashed)) and two fibers of 0.5 mm diameter, for a rectangular tile and reflectivity of 0.8 for the wrapping

13. Light yield taking into account the trapping mechanism, for varying refractive index of the cladding, in a rectangular tile with reflectivity of 0.8 of the wrapping

14. Light yield for a rectangular tile with reflectivity 0.8 of the wrapping, trapping included ($n_{clad} = 1.49$), using totally diffuse reflection

15. Light yield for a slanted tile with reflectivity 0.8 of the wrapping, trapping included ($n_{clad} = 1.49$), using totally diffuse reflection

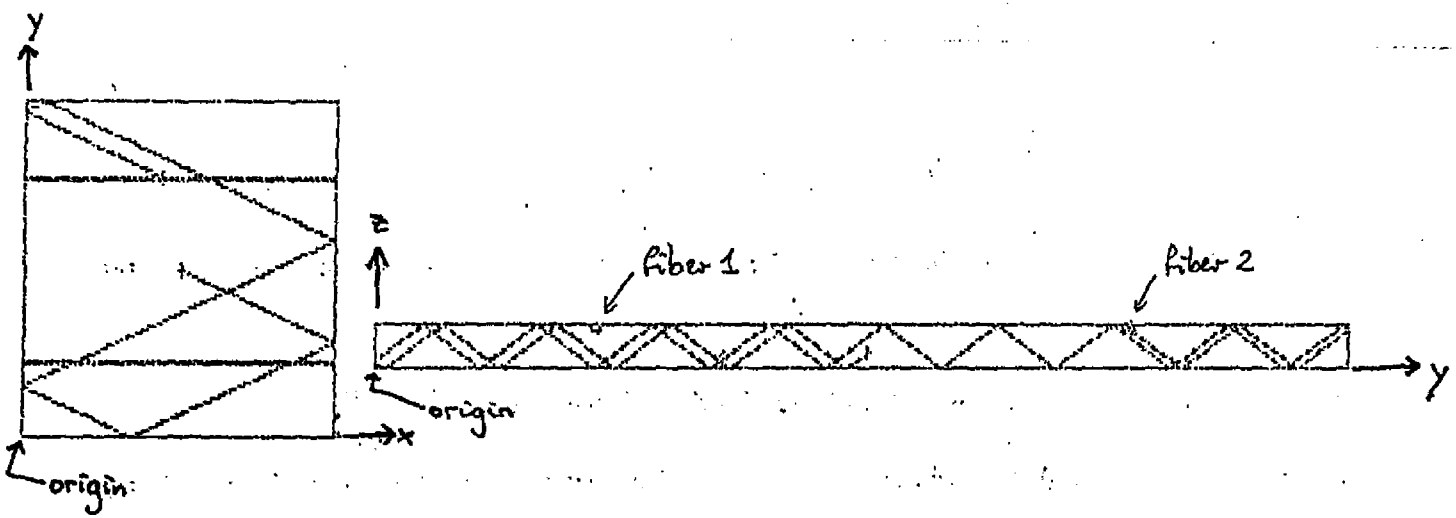


Fig. 1

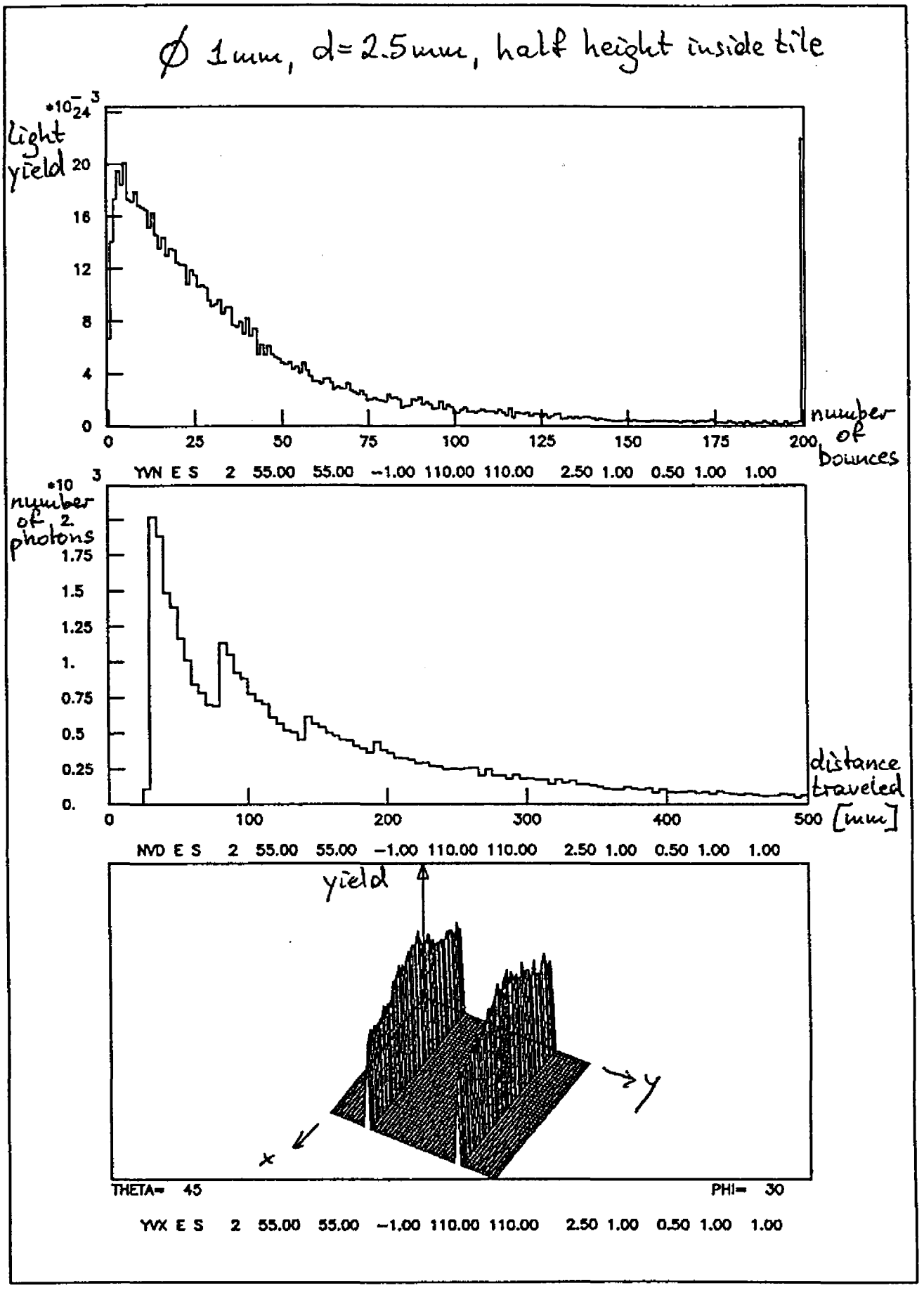

Ø 1mm, d=2.5mm, half height inside tile
*10⁻³
Light yield
20
16
12
8
4
0
0 25 50 75 100 125 150 175 200
number of bounces
YVN E S 2 55.00 55.00 -1.00 110.00 110.00 2.50 1.00 0.50 1.00 1.00
*10³
number of photons
2.
1.75
1.5
1.25
1.
0.75
0.5
0.25
0.
0 100 200 300 400 500
distance traveled [mm]
NVD E S 2 55.00 55.00 -1.00 110.00 110.00 2.50 1.00 0.50 1.00 1.00
yield
y
x
THETA= 45
PHI= 30
YVX E S 2 55.00 55.00 -1.00 110.00 110.00 2.50 1.00 0.50 1.00 1.00

Fig. 2a

Ø 1mm, d=2.5mm, half height at sides

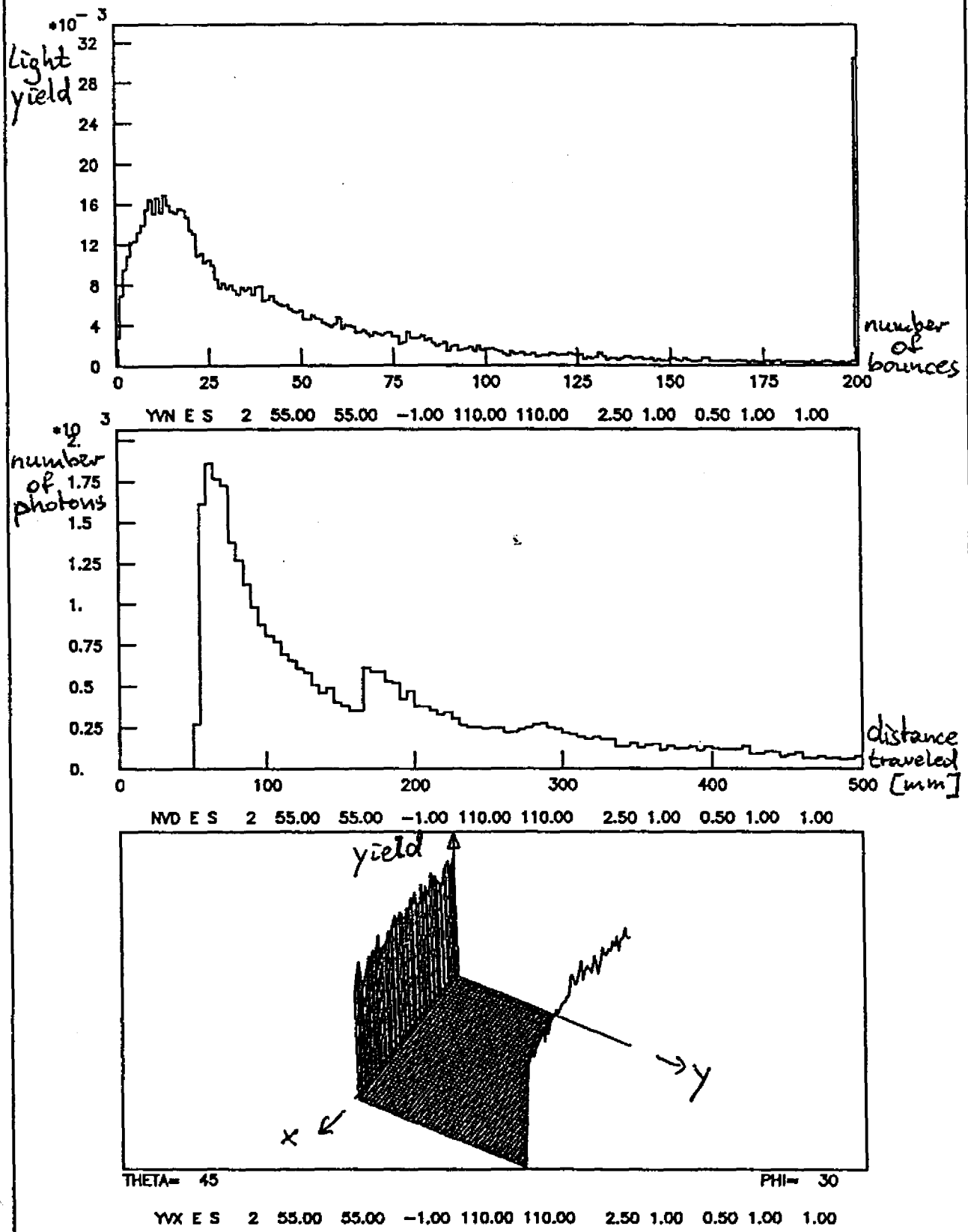


Fig. 2b

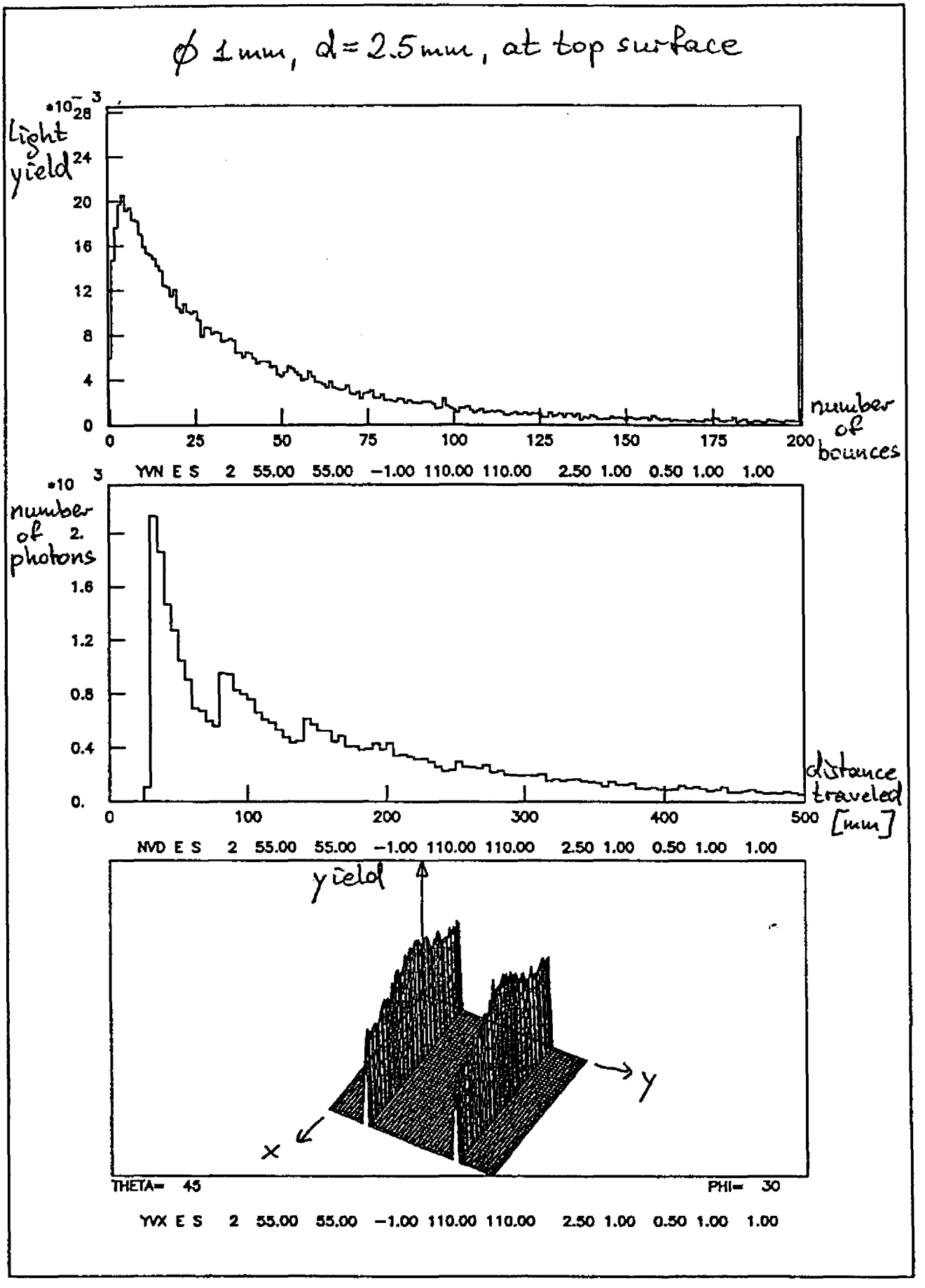

ϕ 1mm, d=2.5mm, at top surface
*10⁻³
light yield
28
24
20
16
12
8
4
0
0
25
50
75
100
125
150
175
200
number of bounces
YVN E S 2 55.00 55.00 −1.00 110.00 110.00 2.50 1.00 0.50 1.00 1.00
*10³
number of photons
2.
1.6
1.2
0.8
0.4
0.
0
100
200
300
400
500
distance traveled [mm]
NVD E S 2 55.00 55.00 −1.00 110.00 110.00 2.50 1.00 0.50 1.00 1.00
yield
y
x
THETA= 45
PHI= 30
YVX E S 2 55.00 55.00 −1.00 110.00 110.00 2.50 1.00 0.50 1.00 1.00

Fig. 2c

Ø 0.6 mm, d=2.5 mm, at top surface

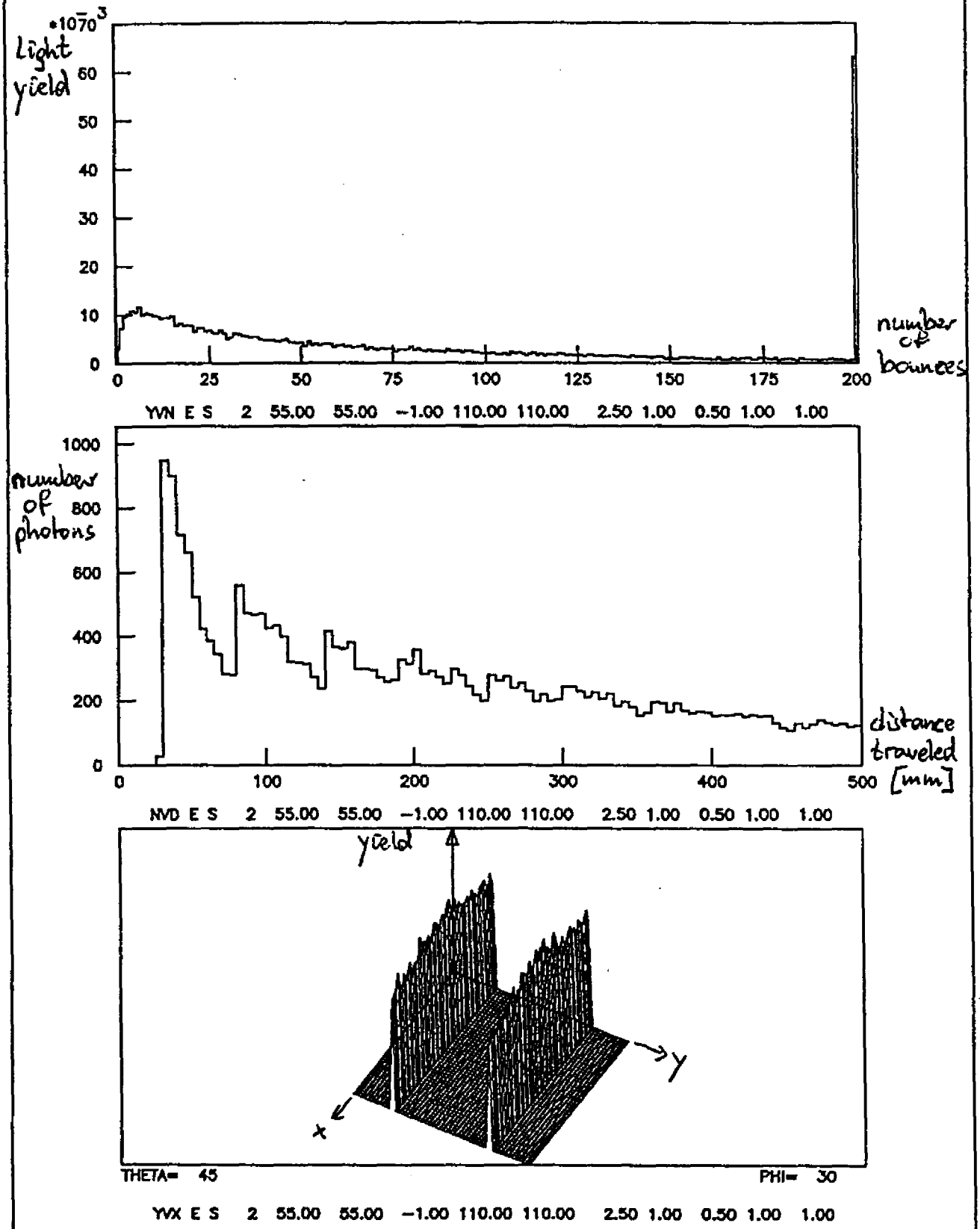


Fig. 2d

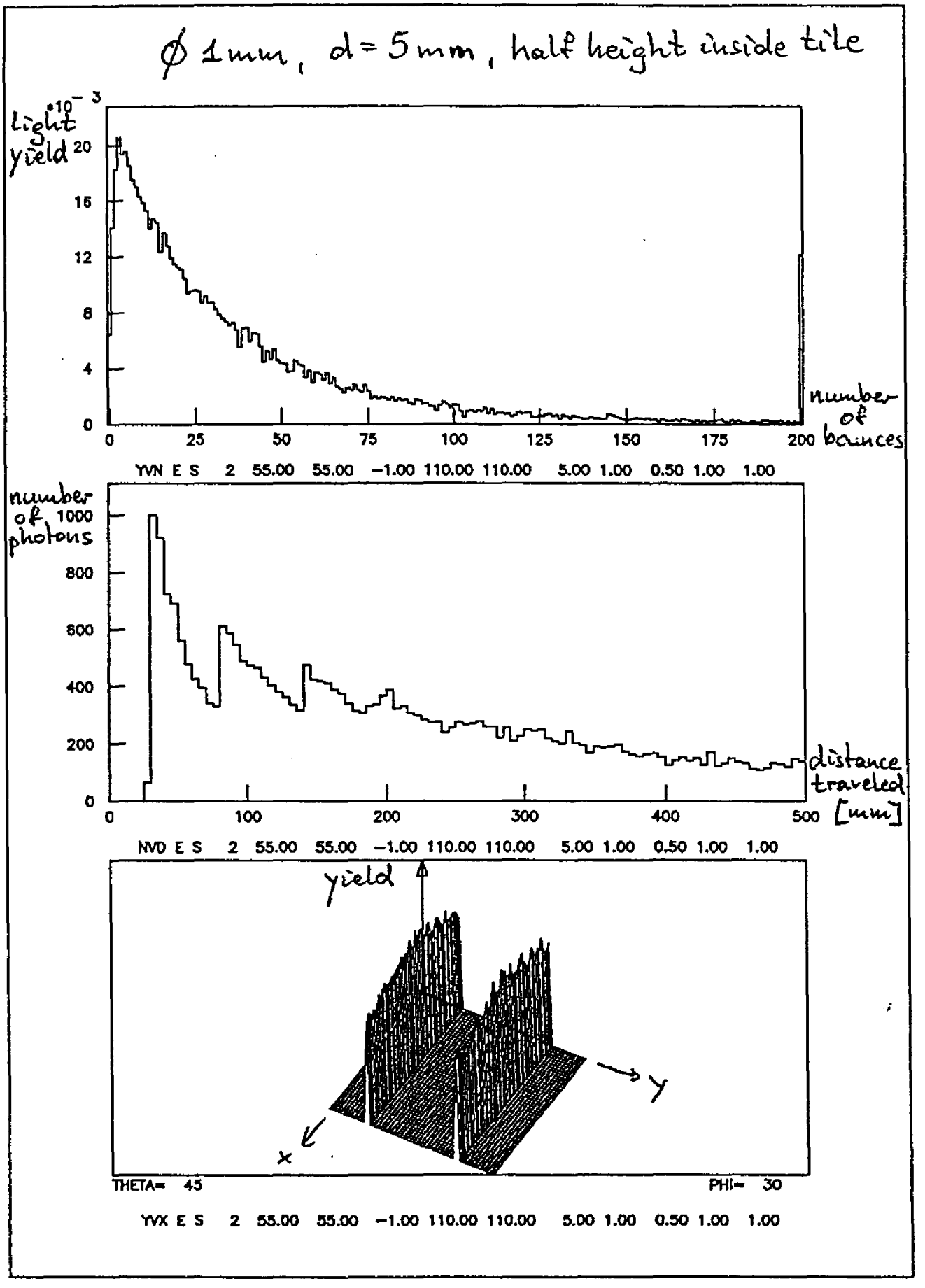
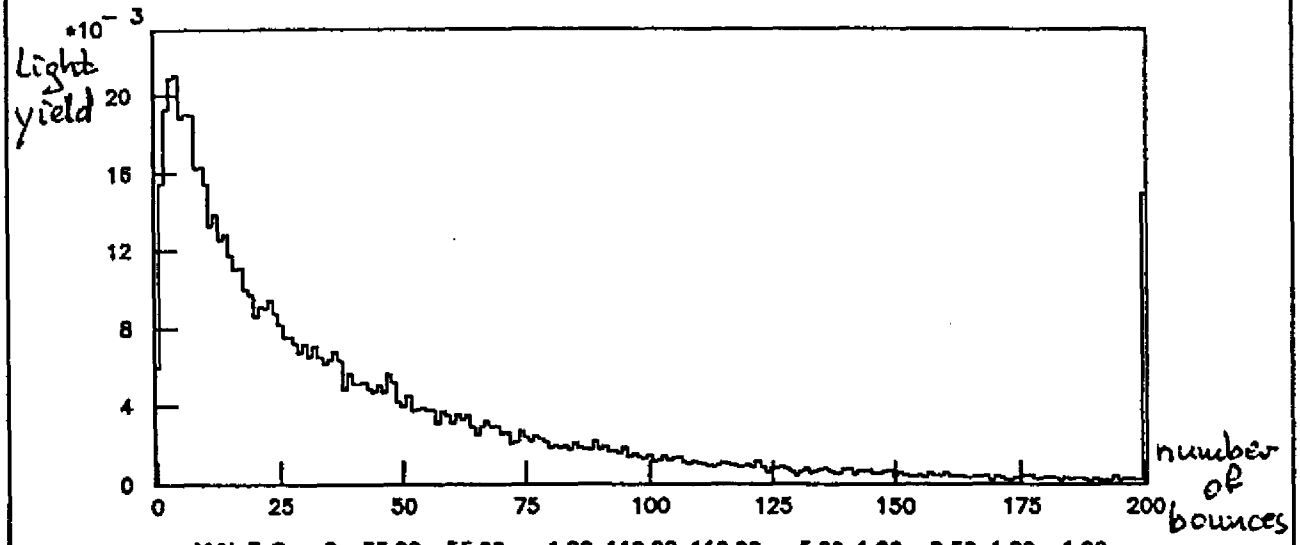
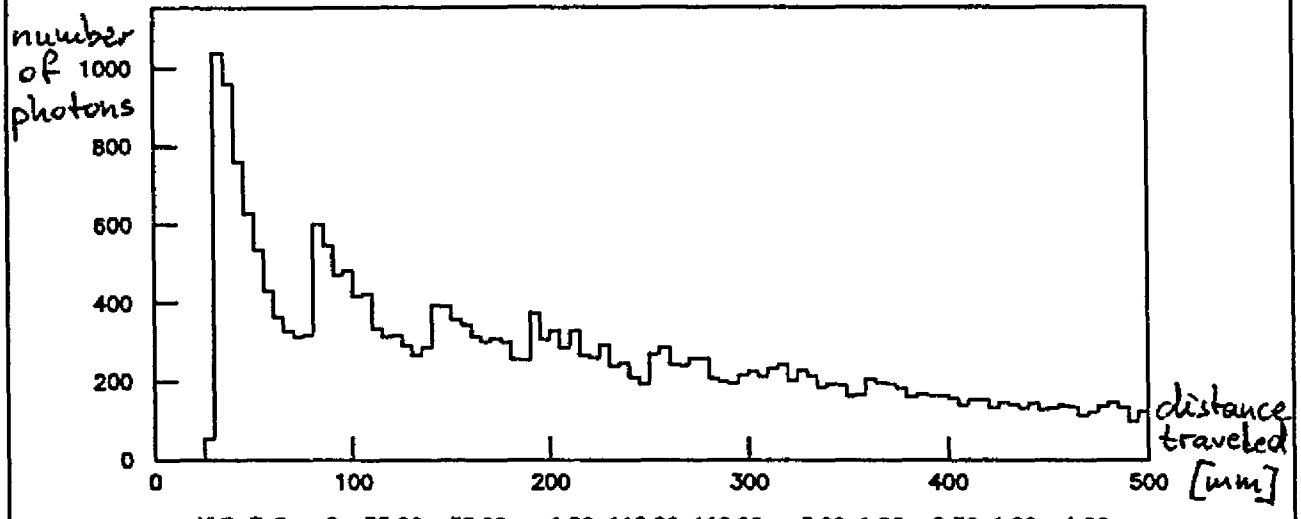

Ø 1mm, d = 5mm, half height inside tile
light yield
*10^-3
20
16
12
8
4
0
0 25 50 75 100 125 150 175 200
number of bounces
YVN E S 2 55.00 55.00 -1.00 110.00 110.00 5.00 1.00 0.50 1.00 1.00
number of photons
1000
800
600
400
200
0
0 100 200 300 400 500
distance traveled [mm]
NVD E S 2 55.00 55.00 -1.00 110.00 110.00 5.00 1.00 0.50 1.00 1.00
yield
y
x
THETA= 45
PHI= 30
YVX E S 2 55.00 55.00 -1.00 110.00 110.00 5.00 1.00 0.50 1.00 1.00

Fig. 2e

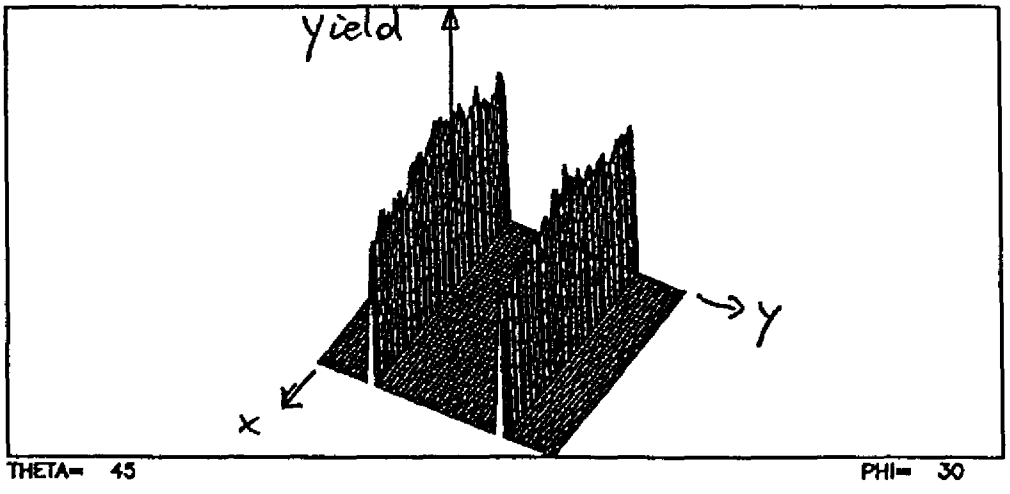
Ø 1mm, d=5mm, at top surface



YVN E S 2 55.00 55.00 −1.00 110.00 110.00 5.00 1.00 0.50 1.00 1.00



NVD E S 2 55.00 55.00 −1.00 110.00 110.00 5.00 1.00 0.50 1.00 1.00



YVX E S 2 55.00 55.00 −1.00 110.00 110.00 5.00 1.00 0.50 1.00 1.00

Fig. 2 f

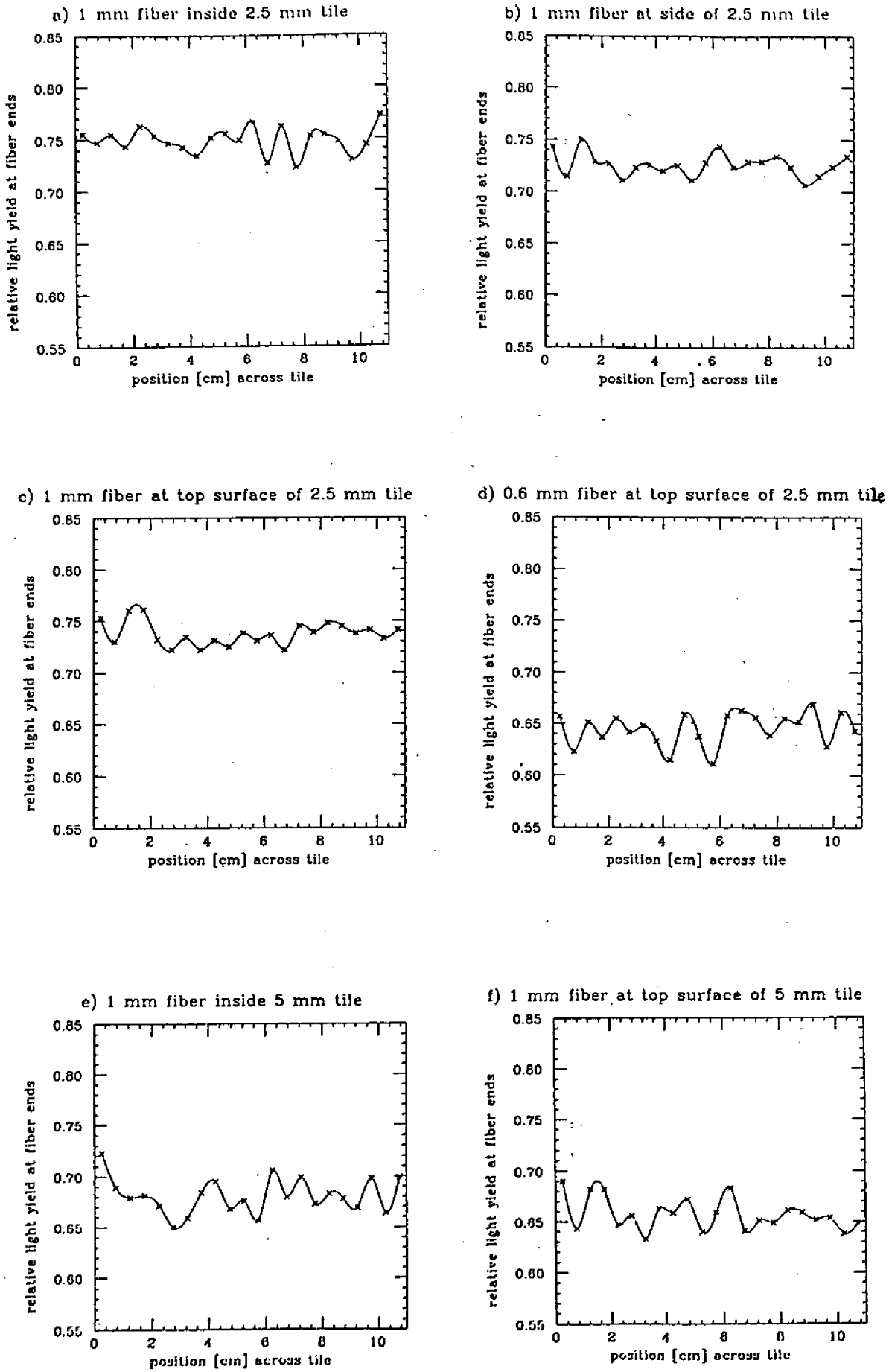

a) 1 mm fiber inside 2.5 mm tile
b) 1 mm fiber at side of 2.5 mm tile
c) 1 mm fiber at top surface of 2.5 mm tile
d) 0.6 mm fiber at top surface of 2.5 mm tile
e) 1 mm fiber inside 5 mm tile
f) 1 mm fiber at top surface of 5 mm tile
relative light yield at fiber ends
position [cm] across tile
0.55
0.60
0.65
0.70
0.75
0.80
0.85
0
2
4
6
8
10

Fig. 3

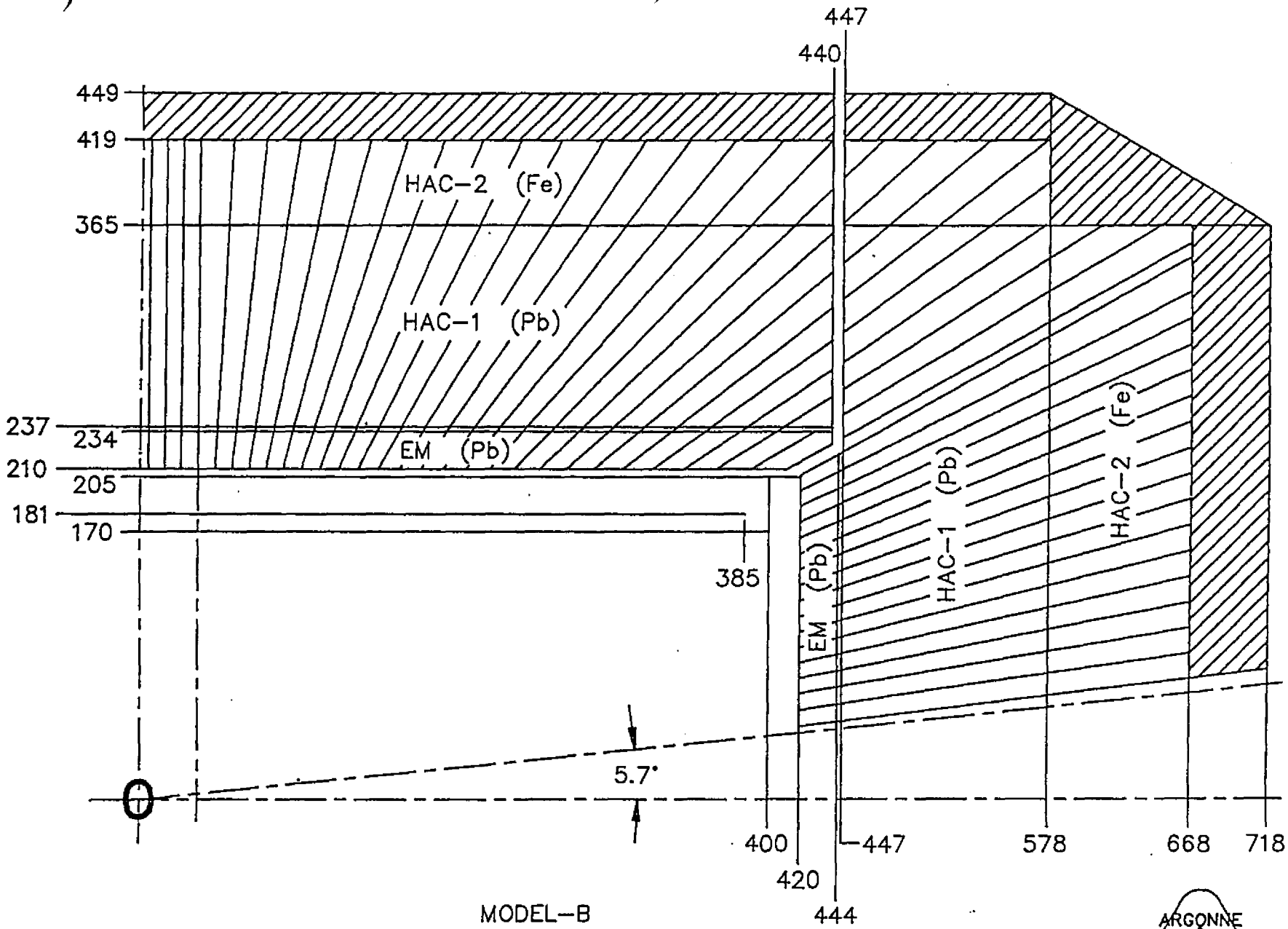
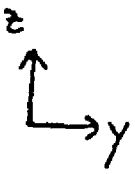


Fig. 4

ARGONNE NATIONAL LABORATORY



variable: base length, width, height,
fiber radii, positions (not fully arbitrarily)
slant angles φ_1, φ_2

fibers run along x,
projections containing x are rectangular

Fig. 5

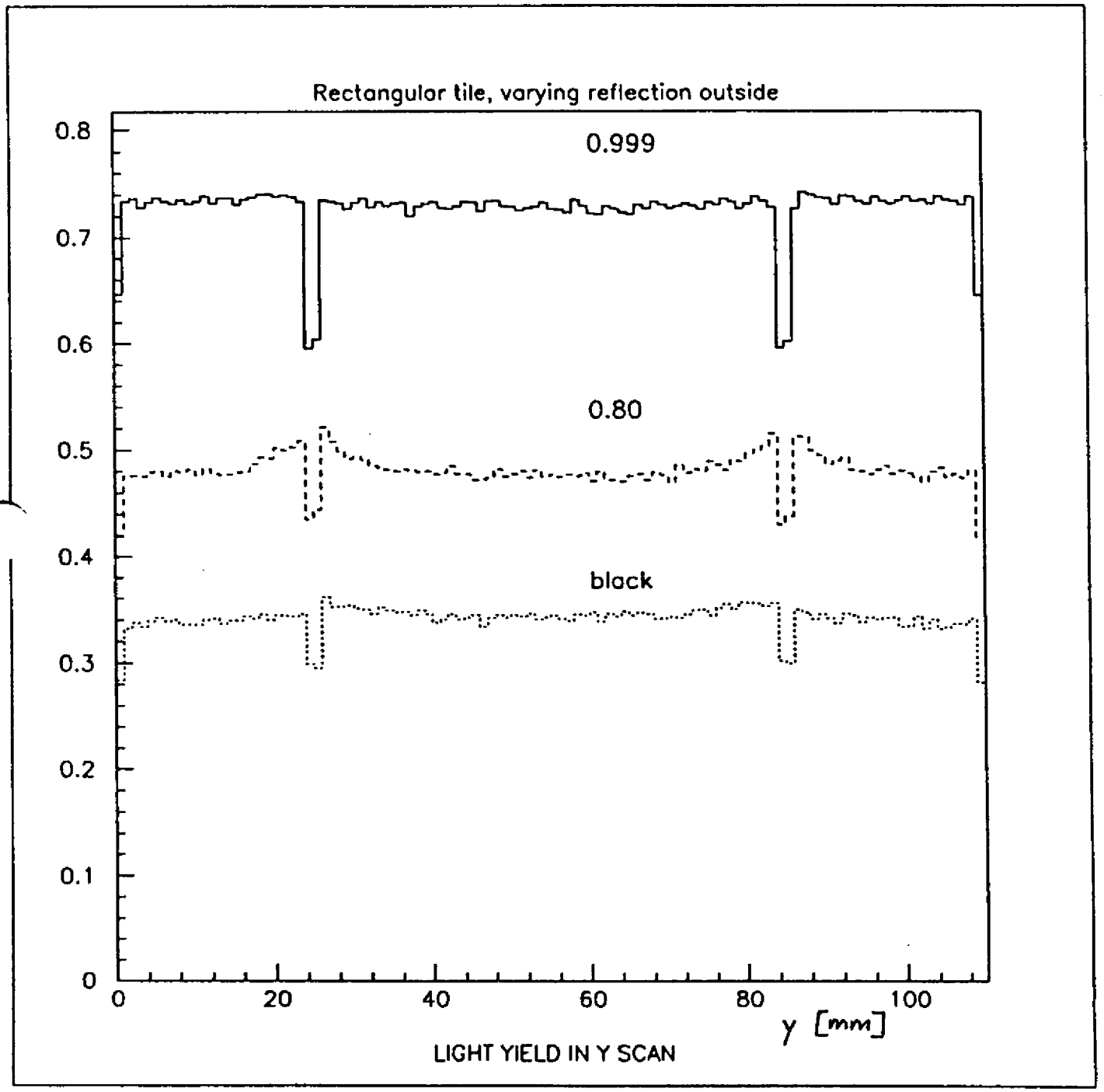

Rectangular tile, varying reflection outside
0.999
0.80
black
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
y [mm]
LIGHT YIELD IN Y SCAN

Fig.6

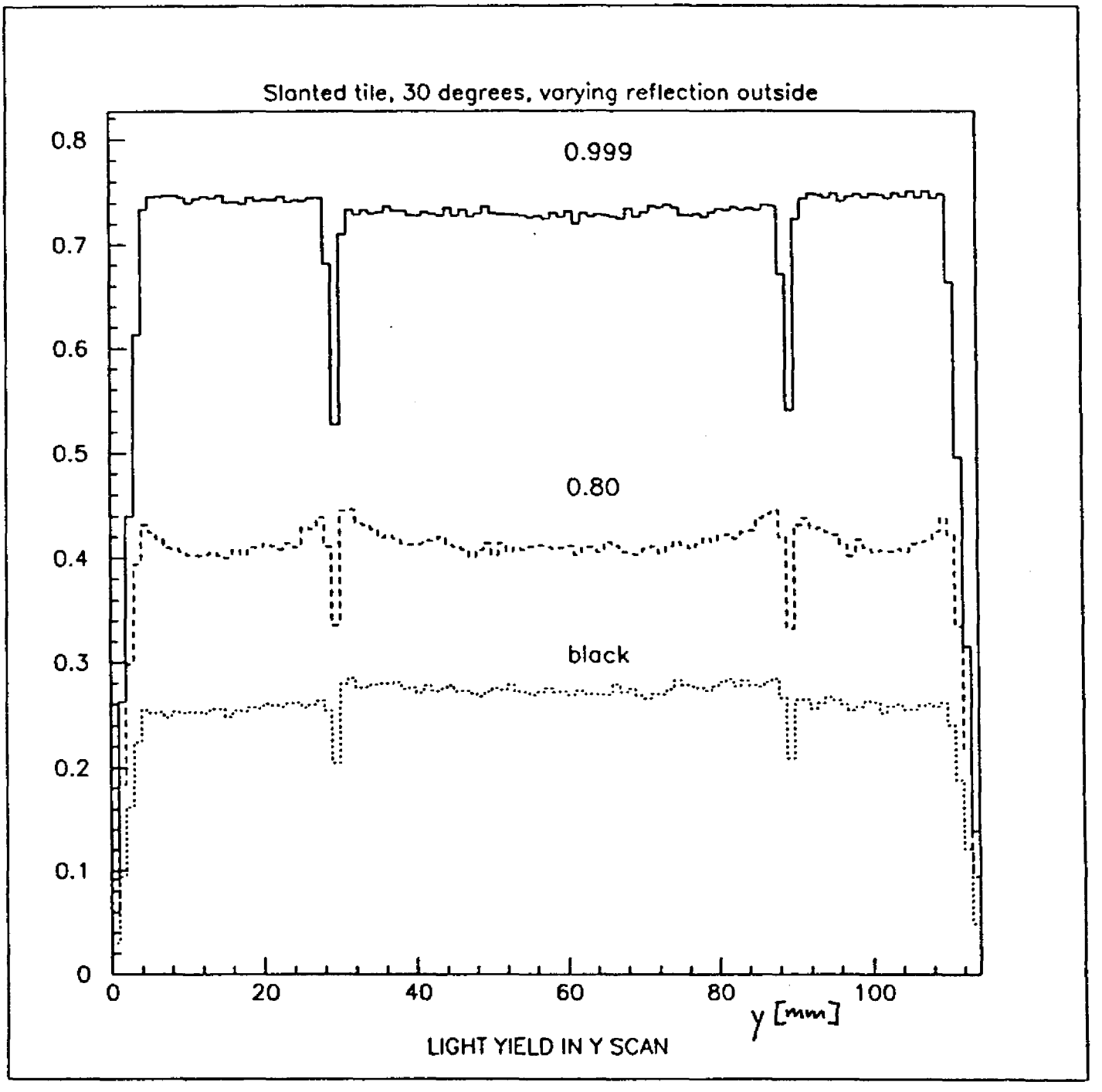

Slanted tile, 30 degrees, varying reflection outside
0.999
0.80
black
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
y [mm]
LIGHT YIELD IN Y SCAN

Fig. 7

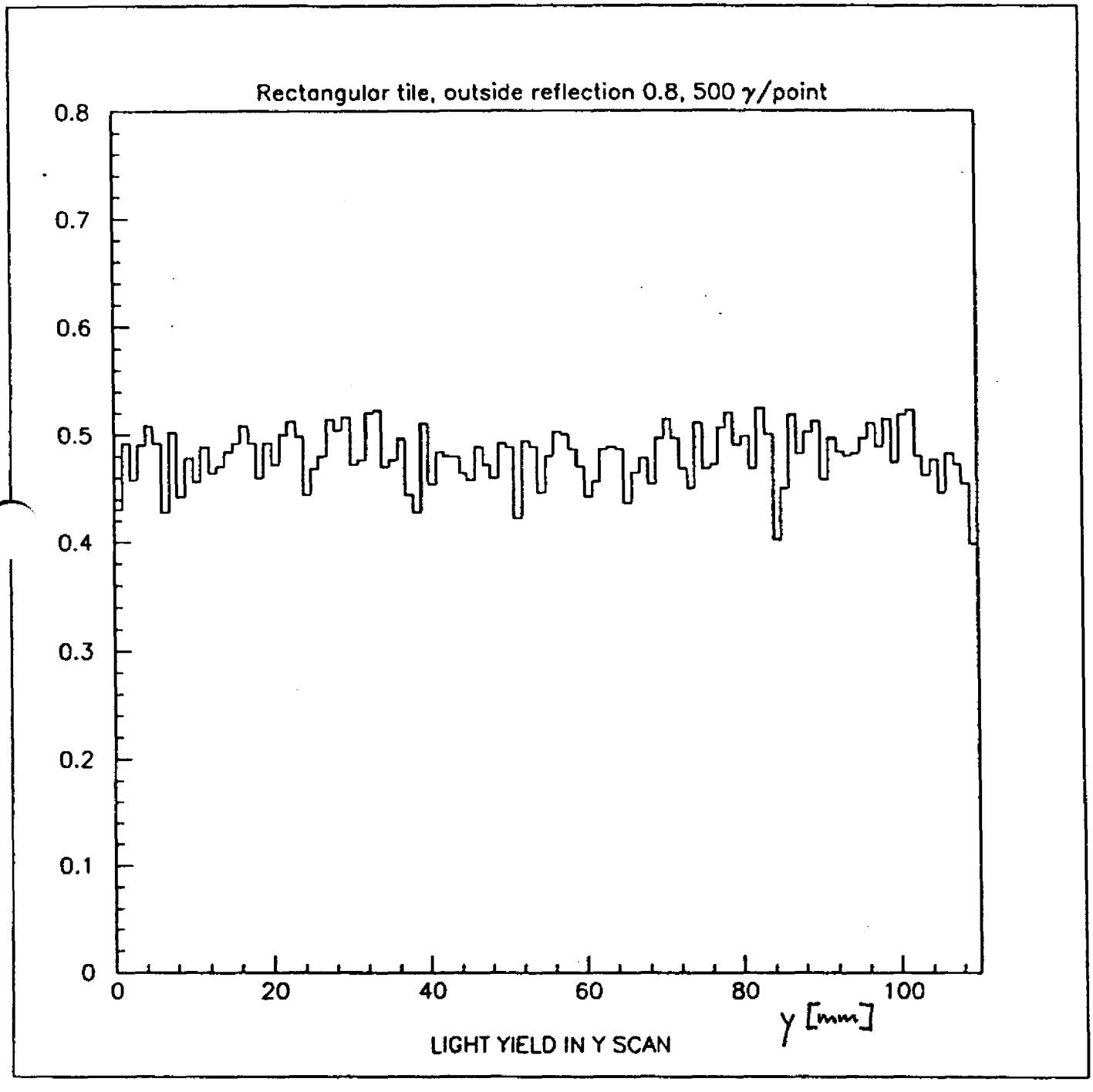

Rectangular tile, outside reflection 0.8, 500 γ/point
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
y [mm]
LIGHT YIELD IN Y SCAN

Fig. 8

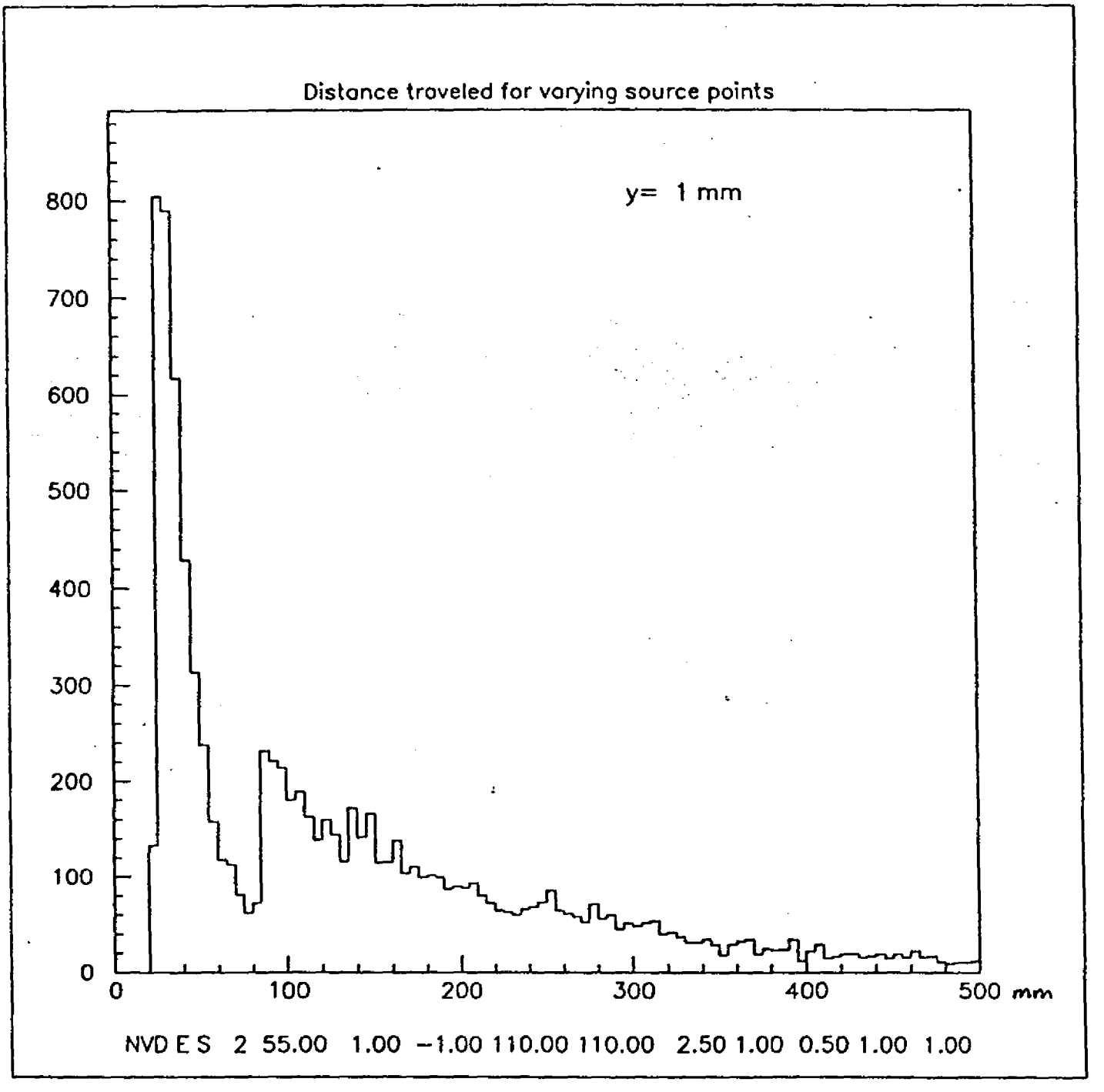

Distance traveled for varying source points
y= 1 mm
800
700
600
500
400
300
200
100
0
0
100
200
300
400
500 mm
NVD E S 2 55.00 1.00 −1.00 110.00 110.00 2.50 1.00 0.50 1.00 1.00

Fig. 9

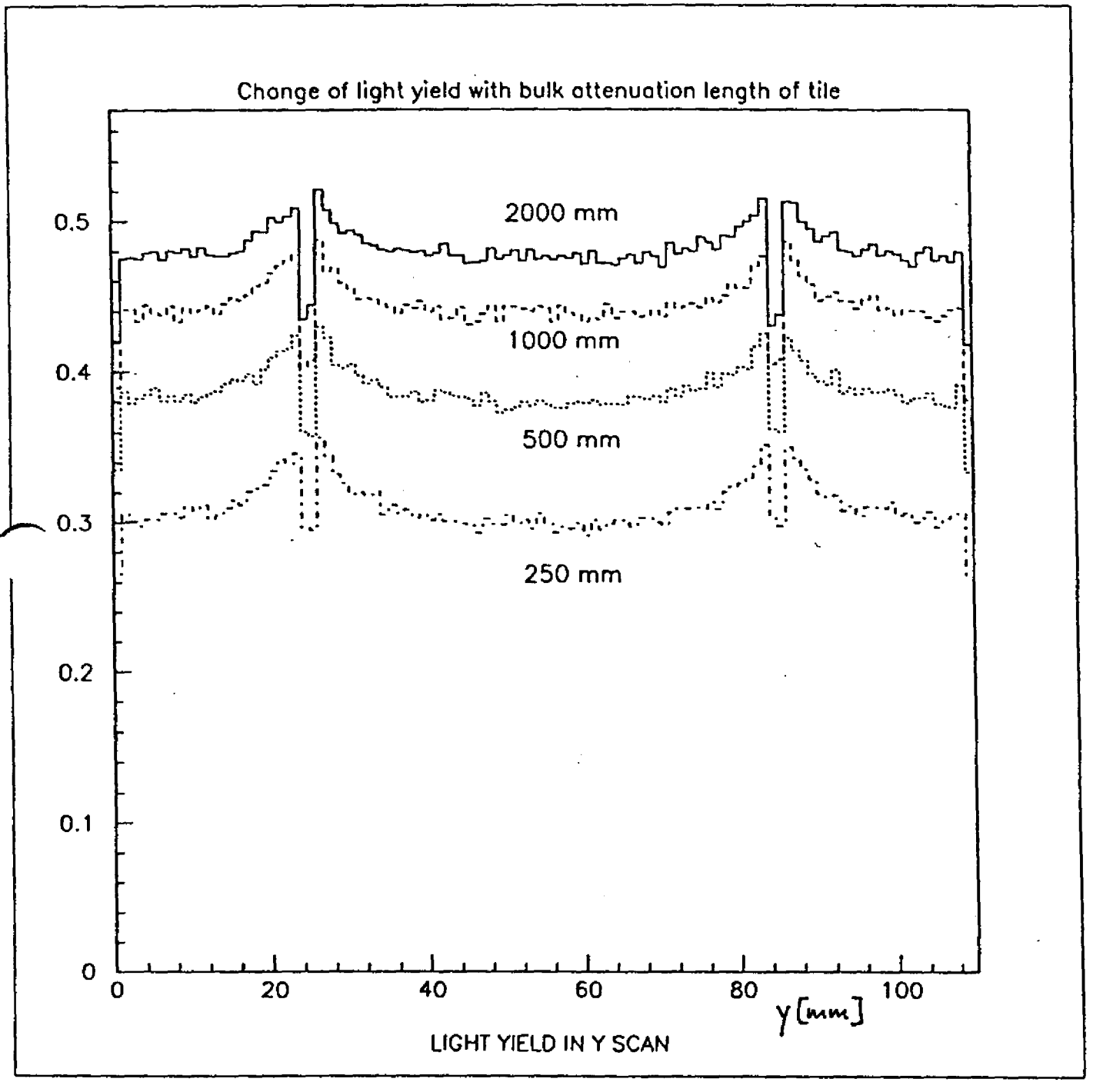

Change of light yield with bulk attenuation length of tile
2000 mm
1000 mm
500 mm
250 mm
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
y [mm]
LIGHT YIELD IN Y SCAN

Fig. 10

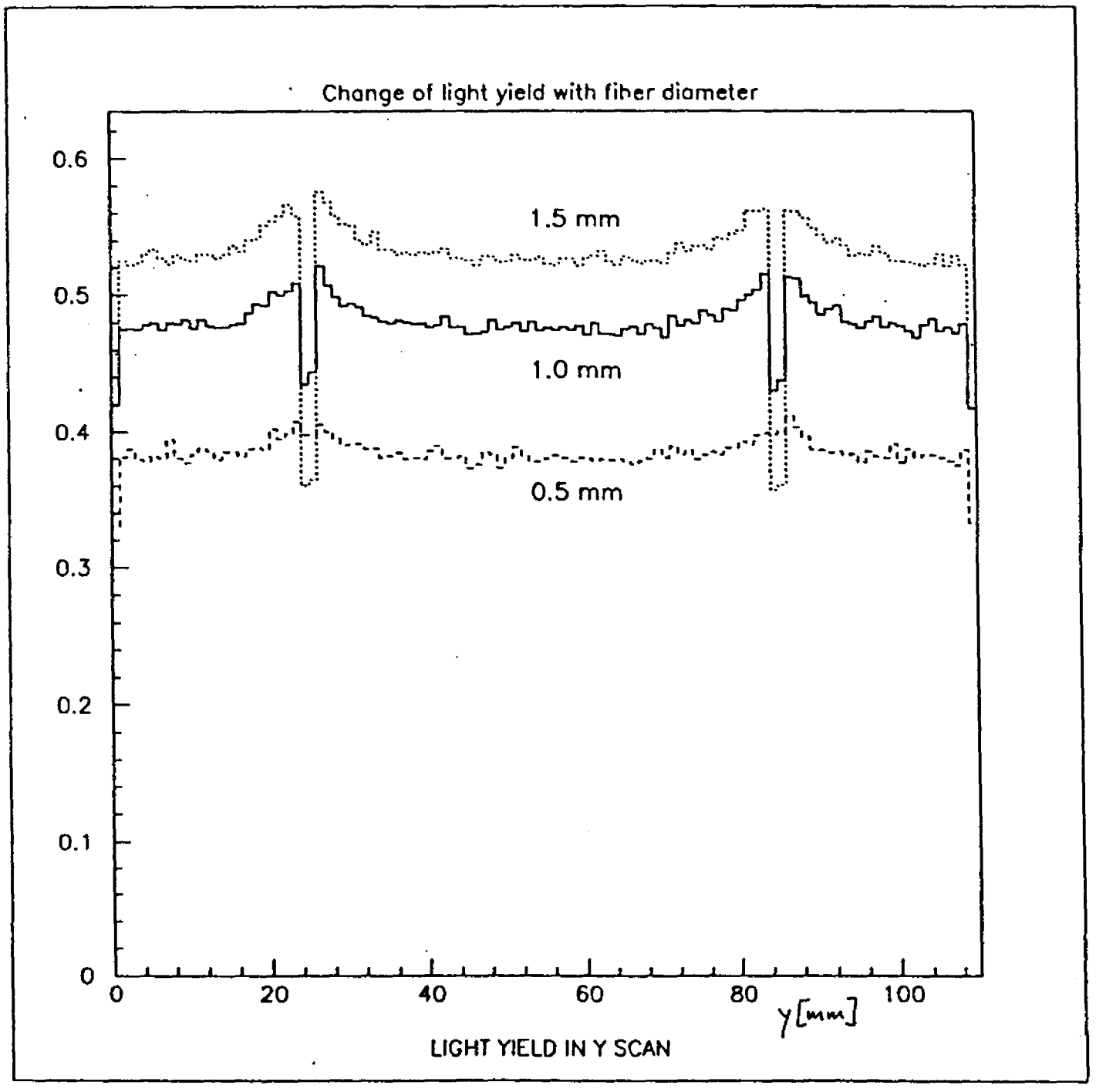

Change of light yield with fiber diameter
0.6
0.5
0.4
0.3
0.2
0.1
0
1.5 mm
1.0 mm
0.5 mm
0
20
40
60
80
100
y [mm]
LIGHT YIELD IN Y SCAN

Fig. 11

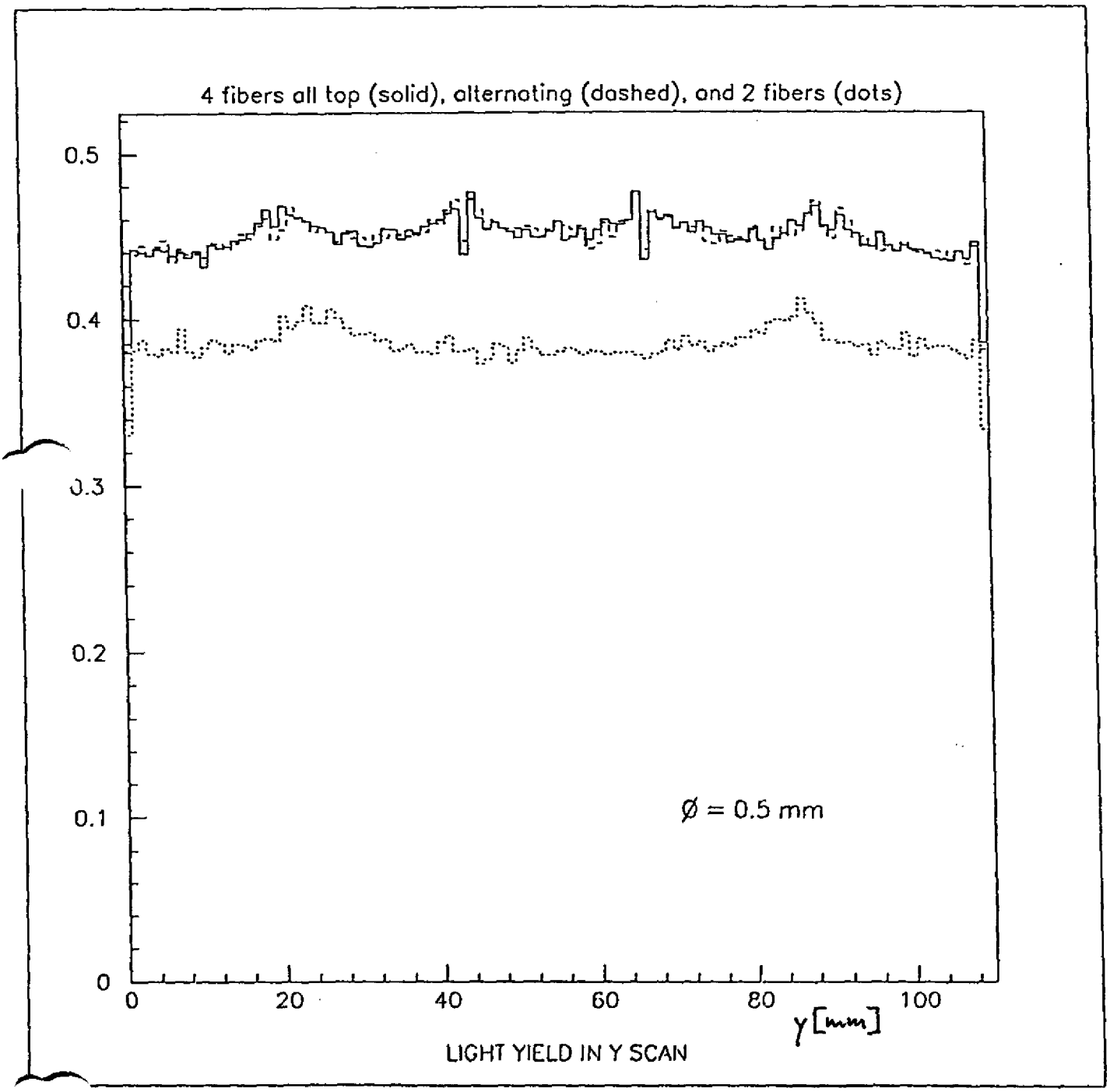

4 fibers all top (solid), alternating (dashed), and 2 fibers (dots)
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
y [mm]
Ø = 0.5 mm
LIGHT YIELD IN Y SCAN

Fig. 12

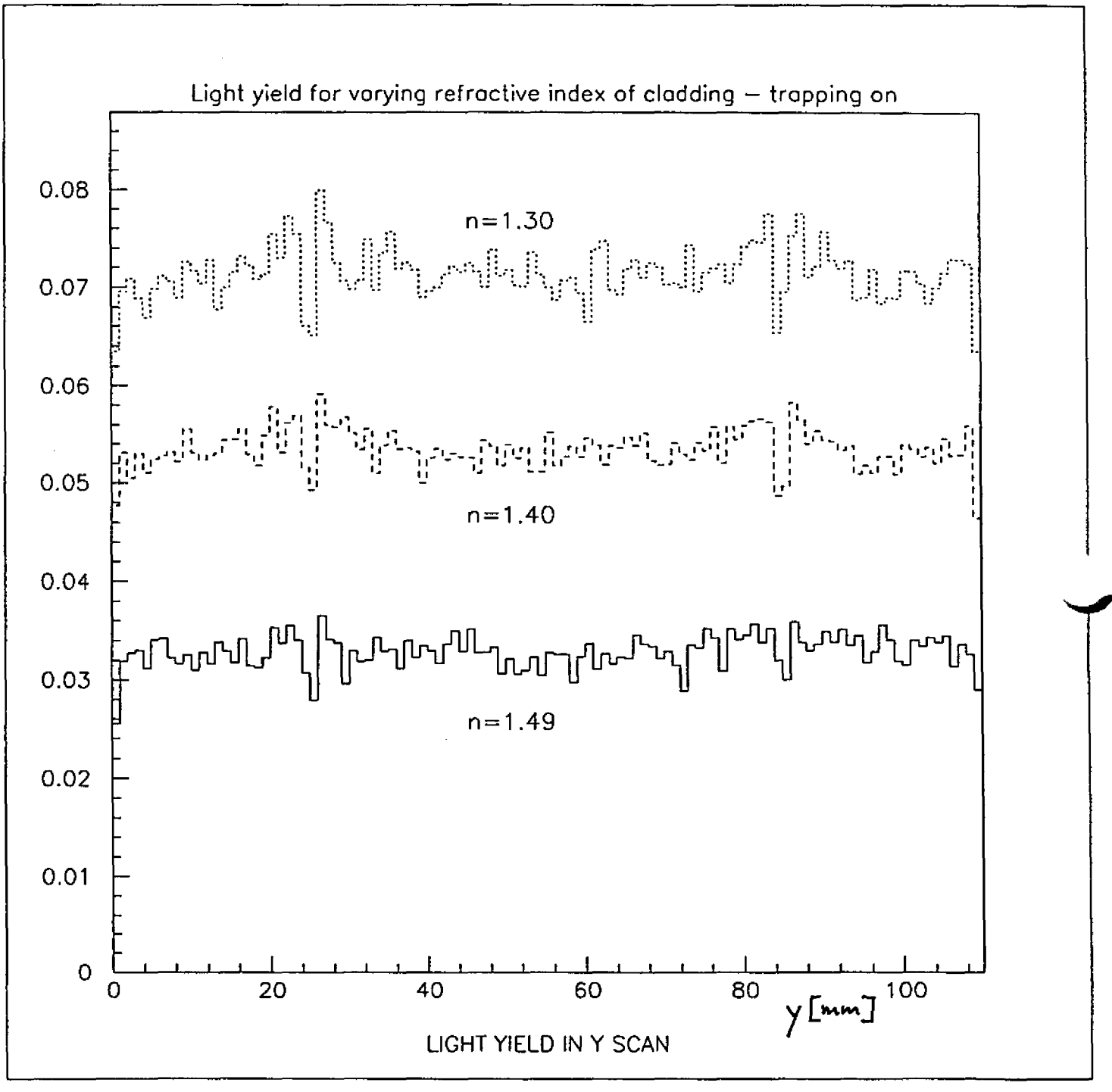

Light yield for varying refractive index of cladding – trapping on
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
n=1.30
n=1.40
n=1.49
0
20
40
60
80
100
y [mm]
LIGHT YIELD IN Y SCAN

Fig. 13

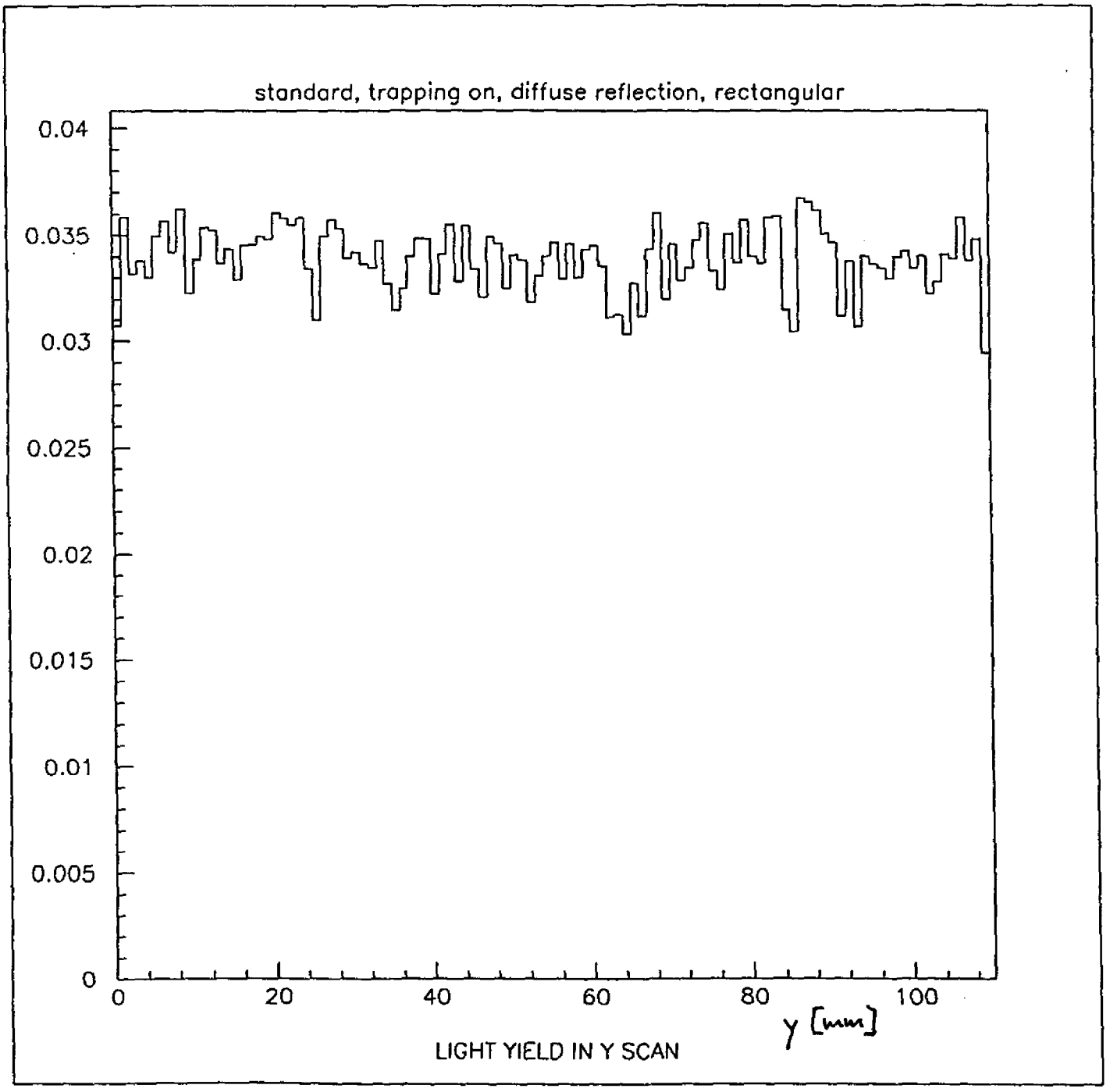

standard, trapping on, diffuse reflection, rectangular
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
20
40
60
80
100
y [mm]
LIGHT YIELD IN Y SCAN

Fig. 14

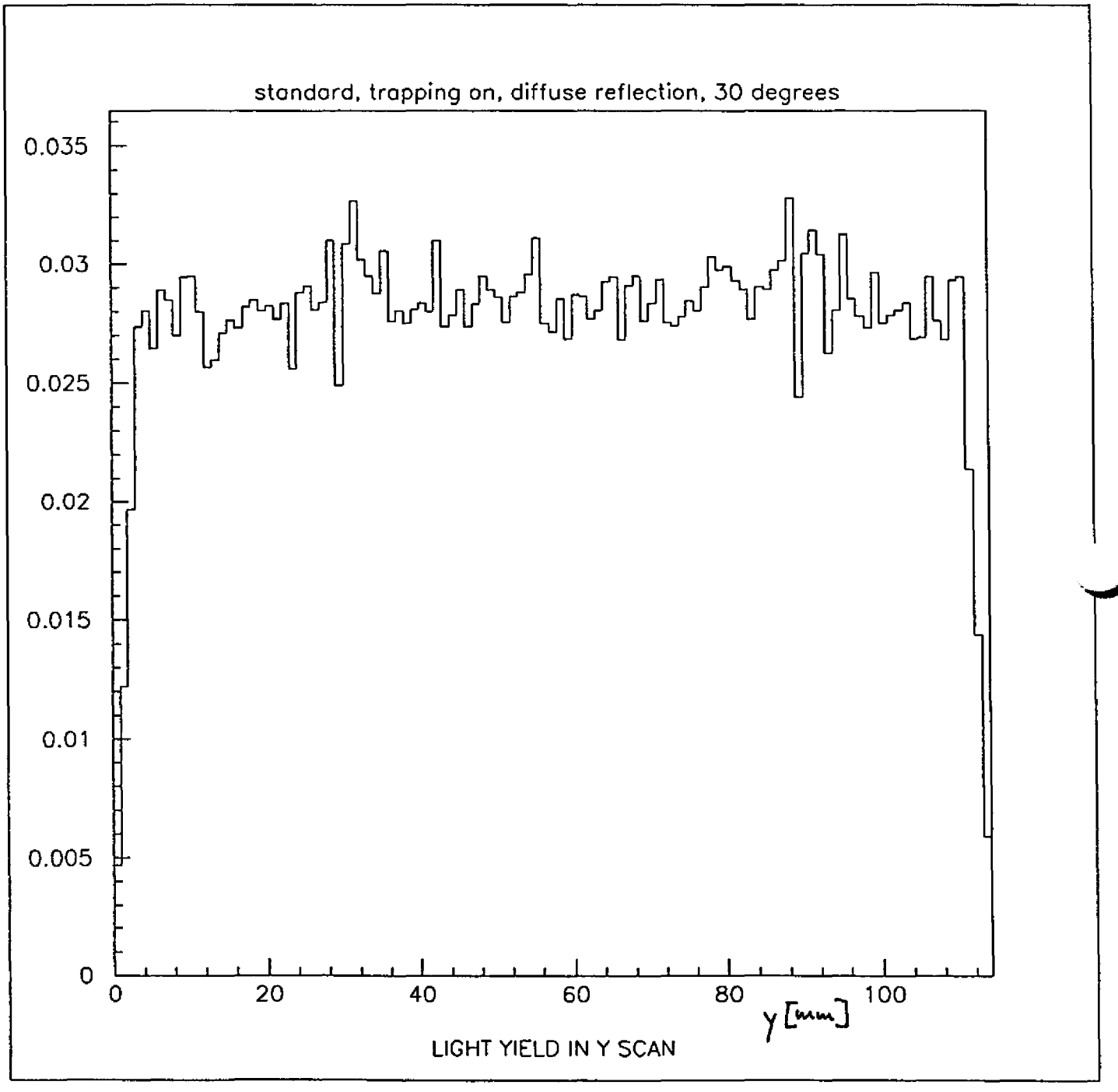

standard, trapping on, diffuse reflection, 30 degrees
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
20
40
60
80
100
y [mm]
LIGHT YIELD IN Y SCAN

Fig. 15