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Light Collection from Scintillation Counters using WLS Fibers and Bars

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Abstract. Several methods of collecting light on scintillation counters using WLS fibers and WLS bars were studied. Nearly 20 prototype counters with different designs and with sizes ranging from $14\times11\times1.3\text{cm}^3$ to $105\times60\times1.3\text{cm}^3$ have been tested using cosmic muons and radioactive source. The efficiency of light collection on number of photoelectrons, uniformity of response, and time resolution have been measured. Test results for two new designs of light collection from scintillator based on WLS fibers around perimeter of scintillator plate and WLS fibers placed in machined on scintillator plate deep grooves are presented. Two out of the studied designs have been chosen as the basic options for the DØ muon system upgrade: light collection using two WLS bars for the forward muon scintillation counters and light collection using WLS fibers in deep grooves on scintillator for central area muon counters.

INTRODUCTION

The study of different scintillation counter designs was motivated by the DØ detector muon system upgrade. Counters for the DØ forward muon system are arranged in a projective R-φ geometry for uniform coverage in η and φ with $\Delta\eta = 0.1$, $\Delta\varphi = 4.5°$ segmentation [1]. Such a design leads to substantially different sizes of trapezoidal counters, from $9\times15\ \text{cm}^2$ to $60\times106\ \text{cm}^2$. Usually, different ways of collecting light from scintillator are using for small and large counters, but, it is preferable to use the same design for all counters. The same design simplifies trigger counters plane design and counter production. The forward muon trigger scintillation counters have to provide good time resolution and uniformity of response for better background rejection, to operate in the fringe magnetic field of the DØ superconducting solenoid and toroidal magnet (350 G) and have low cost and simple handling for the production almost of five thousand counters.

The requirement of good magnetic shielding substantially limits the counters design. Previously, two methods were considered: a direct light collection scheme from cut on 45° scintillator plate corner or the use of common lucid light guide. But, for good magnetic shielding, especially from the field parallel to the phototube axis, one must use a small diameter phototube and allow a small opening in the magnetic shield for light input to the phototube. Using wavelength shifting material (WLS), fibers or bars, one can concentrate the light from the scintillator to the smaller cross-section of fibers or bars and to smaller photocathode area. In practical sense, for a photocathode area

2-3 cm^2 and scintillator plate side of more than 20cm^2 the efficiency of light collection using WLS bars is better than for direct methods of light collection. So, direct ways of light collection from scintillator are not presented in this report.

An extensive study of different methods of light collection using WLS fibers and bars for various sizes of counters was provided. Results of this work have been used as a basis for the choice of light collection from scintillator as well as to optimize the counters design for DØ muon system.

MEASUREMENTS OF COUNTER PARAMETERS

Most of measurements were made at FNAL between November 1995 and January 1996 using cosmic muons. A simple CAMAC style test stand was assembled using a VAX-3200 computer and LeCroy analogue-to-digit (ADC) and time-to-digit (TDC) modules. A telescope of 2 or 3 scintillation counters was used to trigger on cosmic ray muons. Two counters with dimensions $15\times15\times1 cm^3$ were placed 50 cm apart with a test counter between them. A third counter with dimensions $5\times5\times1$ cm^3 was placed close to the test counter. For each prototype counter, the following measurements were made:

1. The efficiency of light collection on number of photoelectrons (N_{phe}) using the mean value of the pulse height (charge) for cosmic muons. A Gaussian fit (excepting Landau's tail) was performed for the pulse height spectra. The photomultiplier (PMT) was calibrated in the number of ADC channels per photoelectron using methods:

a) The mean value of single electron spectra for a light emission diode (LED);

b) From the mean value (A) and standard deviation σ using LED: $N_{phe} = (A/\sigma)^2$. This method underestimates N_{phe}, because it does not takes into account fluctuations of secondary emitted electrons from the first dynodes of the PMT .

c) Using a non-efficiency method for LED pulse height spectra:

$$1- \varepsilon = \exp. (- N_{phe}); \qquad N_{phe} = - \ln(N_{pedestal} / N_{total}).$$

where ε is the efficiency, or the probability to have one or more photoelectrons. The most precise method (c) is used as basic; others (a, b) are used for cross-checks.

The same photomultiplier FEU-115M [2], with better than average photocathode quantum efficiency, was used for all N_{phe} measurements. Some counters were designed for use with EMI 1″ PMT, but all data was measured using FEU-115M for better comparisons.

2. The uniformity of response for N_{phe} versus coordinate was measured using cosmic muons. For some counters, the uniformity of response was also studied by measuring PMT current using a radioactive source Ru^{106}. This method is more accurate, but it requires the uniform wrapping of scintillator and is not suitable for some designs with variable scintillator thickness or for variants using large number of WLS fibers. Additional non-uniformity caused by scintillation of thick fiber bundles on these counters is not measurable using the radioactive source.

3. The time resolution, including time shift versus coordinate. A simple constant threshold discriminator was used at a signal to threshold ratio of 5; the resolution of the trigger (0.5ns) is not subtracted.

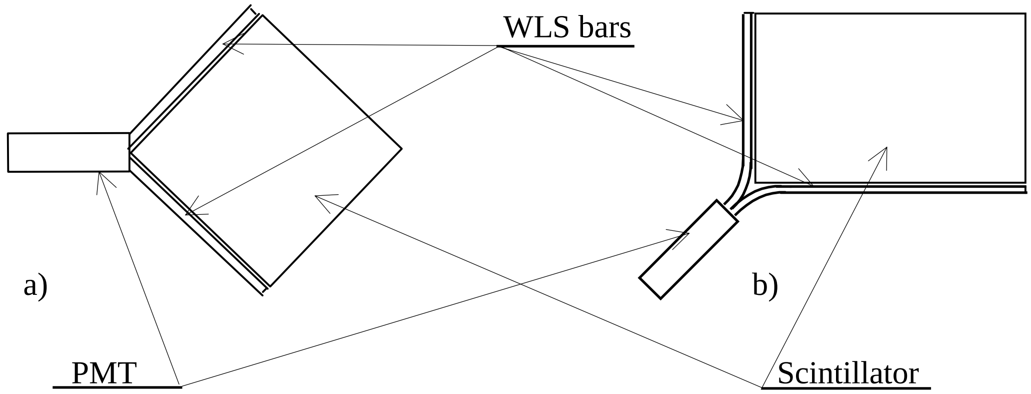


FIGURE 1. Counter design using WLS bars: a) cut at 45^o bars; b) bent at 45^o bars.

COUNTERS DESIGNED USING WLS BARS

Two main design variants were studied (Fig.1), (a) cut on 45° and (b) bent at 45° WLS bars along two scintillator plate sides**.** Some counters were made also in the 4.5° trapezoid shape.

Polymethilmethacrilate (PMMA) scintillator with dopants 1.0%PPO+0.01% POPOP (IHEP, Russia) [3] was used in variant (a), and Bicron 404A plastic is used for less thickness for the same light in variant (b). In both cases, 4.2 mm thick WLS bars are made of PMMA with dopant Kumarin 7 [4]. The decay time is 4 ns, and the absorption length is about 1 m. The opposite to the PMT ends of the WLS bars for (a) and (b) are made reflective using aluminized tape. The PMT FEU-115M with a photocathode

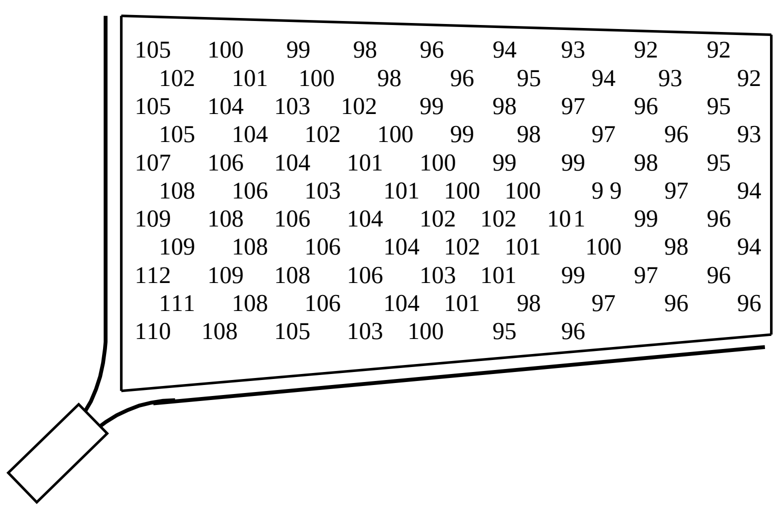
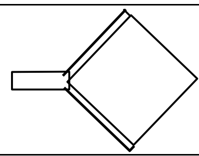
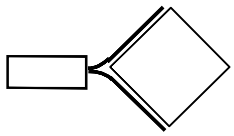
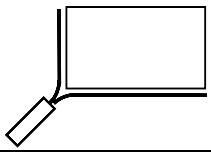
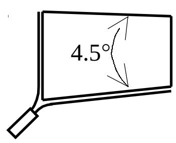
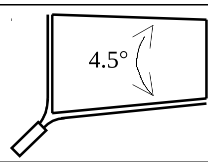
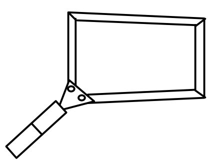
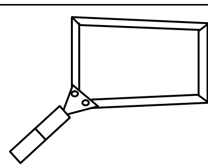


FIGURE 2. The uniformity of light response for counters using WLS bars. Measurements used the radioactive source Ru^{106} (current method). Counter 15, 465×325×12.7 mm^3 , without masking. $\sigma_I/I = 4.9\%$, $I_{max} / I_{min} = 1.22$.

TABLE 1. Test results of counters using WLS bars.

Coun-ter #	Design	Sizes, mm^3 Scintillator	N_{phe} on center	Non-unifor-mity	Timing	
					σ_t ns	Δt ns
7		241×241×22 PMMA scintillator	62	±12%	1.1	2.0
13		137×137×12.7 Bicron 404A	184	±5%	0.7	0.3
14		465×325×12.7 Bicron 404A	99	±9% σ=5.5%	0.9	3.2
15		465×325×12.7 Bicron 404A	115	±7% σ=4.9%	0.8	3.1
19		1054×597×12.7 Bicron 404A	61	±10% σ=7.1%	1.2- -1.6	7.5
21		236×163×12.7 Bicron 404A	75	±10%	0.9	1.5
23		326×236×12.7 Bicron 404A K30 WLS bars	194	±9%	0.7	1.9

diameter 20 mm, quantum efficiency 17%, and rise time 3 ns is used. The scintillator and WLS bars are wrapped in Tyvek material for better light collection, and in black paper for light tightness. A mechanically designed variant consists of aluminum container, made of two 1mm thick plates, an extruded profile around the perimeter of the counter, and a stainless steel part, welded to the soft steel magnetic shield for connection to aluminum container. Variant (a) was primarily tested. For this variant, it is difficult to provide a good magnetic shielding for the photocathode area of the PMT. For this type of PMT, it is necessary to extend the mu-metal magnetic shield for at least

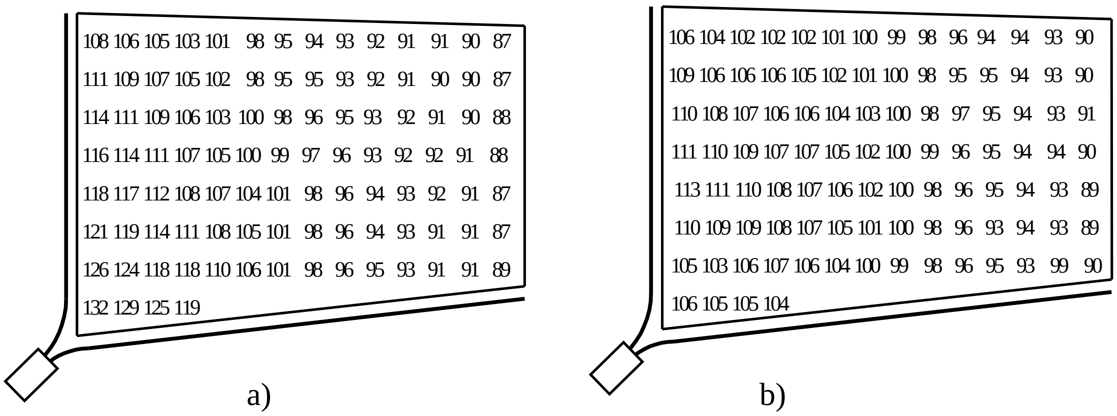


FIGURE 3. The uniformity of light response for counters using WLS bars. Measurements used the radioactive source Ru^{106}. Counter 1054×597×12.7 mm^3. a) without masking. σ_I/I=9.6%, I_{max}/I_{min}=1.5. b) with masking using paper wedges between bars and scintillator plate. σ_I/I=6.1%, I_{max}/I_{min}=1.26; ($I_{without\ mask}/I_{with\ mask}$)=1.2.

22 mm above the photocathode. Next, this variant must have optical contact between the cut on 45° bar ends and the photocathode due to non-perpendicular light output from the bar ends. This requirement is not acceptable for large number of counters because of its low reliability. The variant (b) is made to be free from these disadvantages.

The uniformity of light response for counters using WLS bar is shown in Fig.2 and Fig.3. Measurements of PMT current (I) are made using the radioactive source Ru^{106}. All data are normalized to a mean value. It is easy to improve the uniformity of counters by a factor of 1.5 by placing white paper wedges between the WLS bars and the scintillator plate. This masking decreases the light in the hot area in the corner of the scintillator near the PMT, but also decreases the average light output level by 20% . Table 1 shows the overall results for counters using WLS bars. The non-uniformity is shown in terms of $\Delta=(N_{phe\ max}-N_{phe\ min})/(N_{phe\ max}+N_{phe\ min})$ for all measured points for the measurements using cosmic muons, and in terms of σ (dispersion) for the measurements using a radioactive source. The timing results are presented in terms of σ_t-dispersion for the Gaussian fit to the time distributions, and the Δt-maximum value of the timing shift versus coordinates. All tested counters demonstrated good efficiency of light collection, much more than 30 photoelectrons, which is specified as the minimally required value for the DØ muon system, and exhibit good timing.

COUNTERS USING FIBERS IN FLAT GROOVES

These counters are designed similar to the existing DØ Cosmic Cap counters [5]. WLS fibers are placed on the top side of the scintillator plate in machined 4mm wide grooves, 4 fibers in each groove, with a 4 mm space between grooves, so ½ of the

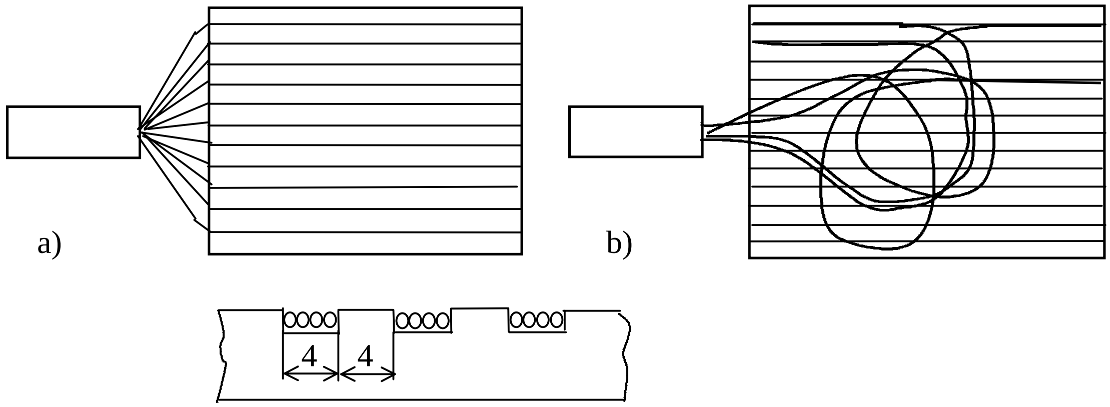


FIGURE 4. Design options for counters using flat grooves. a) one set of fibers in each groove; b) two set of fibers in each groove.

scintillator plate is covered by fibers (Fig.4). For some variants, the spacing between grooves is made 2 mm wide at the edges of scintillator for best uniformity, or two set of fibers are placed in each groove. Each set covers ½ of the groove length. The ends of fibers opposite to PMT as well as this side of the scintillator plate are made reflective using aluminized tape. Bicron 404A scintillator and 1mm diameter Bicron BCF92 WLS fibers with decay time 2.7 ns and an absorption length of 2.7 m are used.

Table 2 shows the test results for counters using flat grooves. Values are quoted as in Table 1. This design shows 36-64 photoelectrons and generally good timing. The use of so many fibers, up to 320 per counter, is not the best choice, and not only for cost and handling. Fiber bundles scintillation decrease in some cases counter characteristics such as the uniformity of response and the timing accuracy.

COUNTERS WITH FIBERS AROUND THE SCINTILLATOR

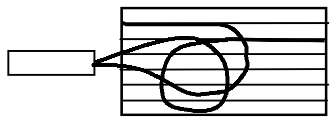
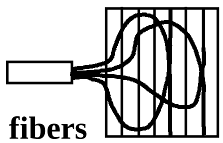
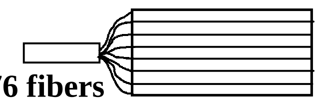
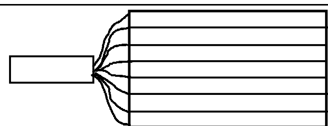
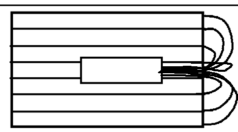
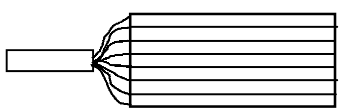
Designs of counters with fibers around the perimeter of scintillator plate are shown in Fig.5. Bicron 404A scintillator and 1mm diameter Bicron BCF92 WLS fibers are used. The main idea of this design is simple: ~1/6 of total light in scintillator plate goes to each of the 6 sides inside internal reflecting cones; the smaller is the side, the higher is the brightness of light to this side. Fibers are oriented to collect light to the small sides of plate. So, 4 of 6 sides are covered using only 12 (or less in some tests) fibers for 12.7 mm thick scintillator (~4/6 of total light goes to these fibers). Both ends of the fibers are glued in a lucid tube. This assembly is diamond-cut and placed at the PMT photocathode.

The advantages of this design, compared to the flat grooves design are as follows:

- Higher efficiency of light collection using smaller number of fibers;
- It is not necessary to cut, polish and mirror the ends of fibers opposite to the PMT;
- A smaller diameter PMT may be used;
- It is easy to place PMT on top of the scintillator, the small number of fibers makes fiber assembly more flexible.

Fibers are longer in this design, however their length is equal to the perimeter of the

TABLE 2. Test results of counters using WLS fibers in flat grooves.

Coun-ter #	Design	Sizes,mm^3 Scintillator	N_{phe} on center	Non-unifor-mity	Timing	
					σ_t ns	Δt ns
5	 **320 fibers**	465×325×12.7 PMMA scintillator	36	±18%	1.1 (> 2 with bund-les)	1.2
8	 **320 fibers**	465×305×12.7 Bicron 404A	40	±11%	1.1	1.2
6	 **76 fibers**	229×152×12.7 Bicron 404A	55	±5%	0.7	1.1
10	 **180 fibers**	470×356×12.7 Bicron 404A	60	–	1.1	2
12	 **160 fibers**	457×305×12.7 Bicron 404A	54	±7%	–	–
17	 **160 fibers**	914×318×12.7 Bicron 404A	64	±21%	0.8	4.7

scintillator**.** This design is therefore good for counters that are not very large. A mechanical design is required to protect the fibers from damage. The mechanically designed variant is similar to the counters with bars and consists of an aluminum container made of two 1mm thick plates and an extruded profile around the perimeter of the counter. The PMT is placed on top of the counter.

Test results of counters using fibers around the scintillator are shown in Table 3.

The number of photoelectrons for this design is more than that obtained using flat grooves for the same size counter but less than for design using bars. Counters using 12 fibers have 1.8 times less light yield for sizes 465×324×12.7mm^3 and 1.2 times less for sizes 1054×597×12.7 mm^3 compared to a design using WLS bars. The difference is less for larger counter because of less than for fibers absorption length of bars. Timing for this design is 10-20% worse as compared to the bars design. Fig.6 shows the light yield on the center of the counter versus the number of fibers for two different size counters. There is a saturation effect for this dependence. It is surprising

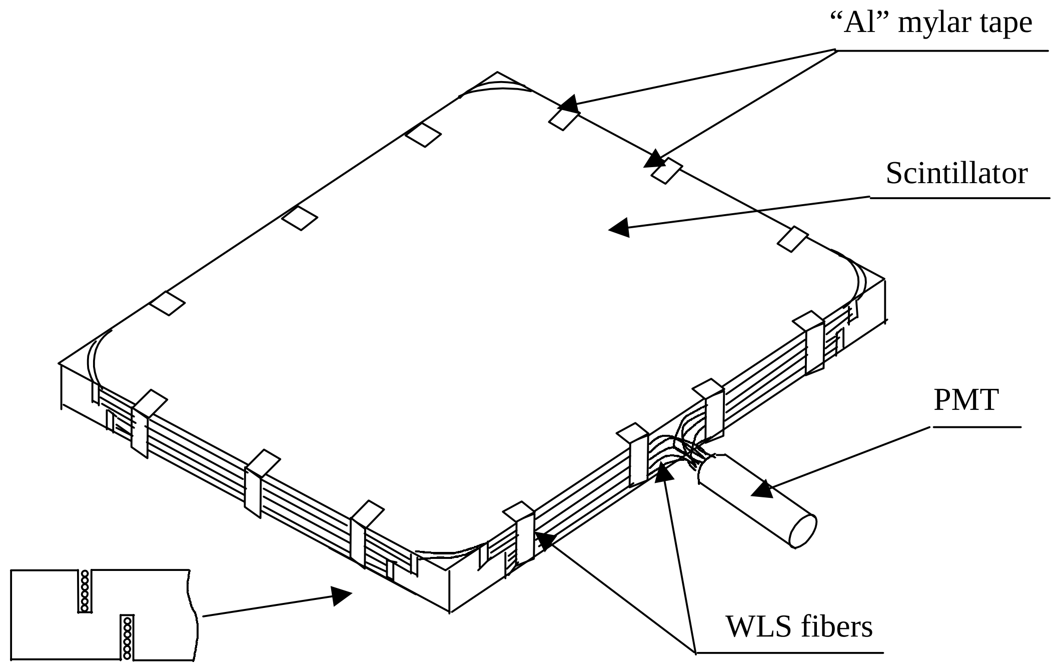


FIGURE 5. Design with fibers around the counter perimeter.

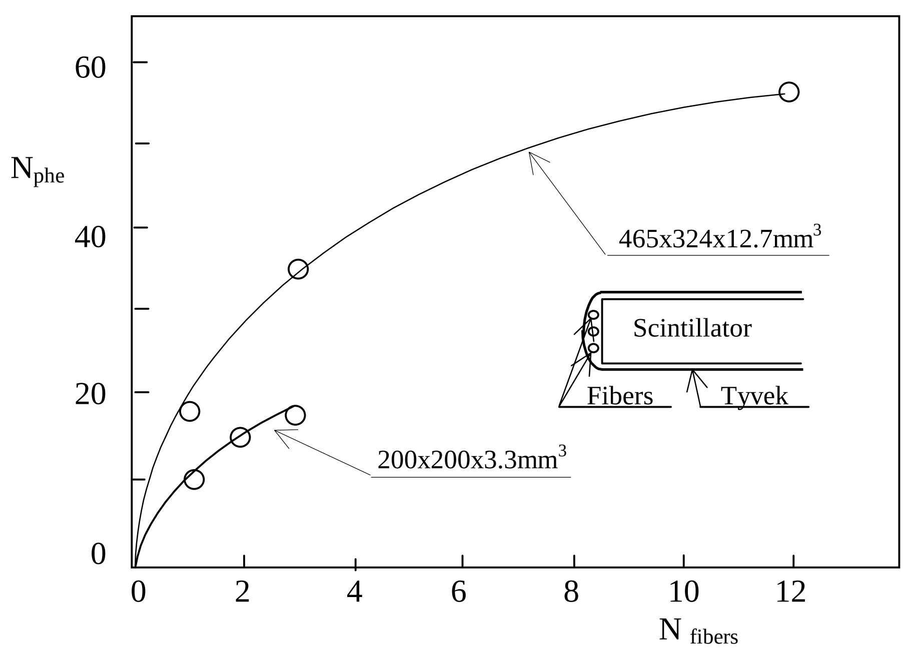


FIGURE 6. Number of photoelectrons versus number of fibers for design with fibers around the counters perimeter.

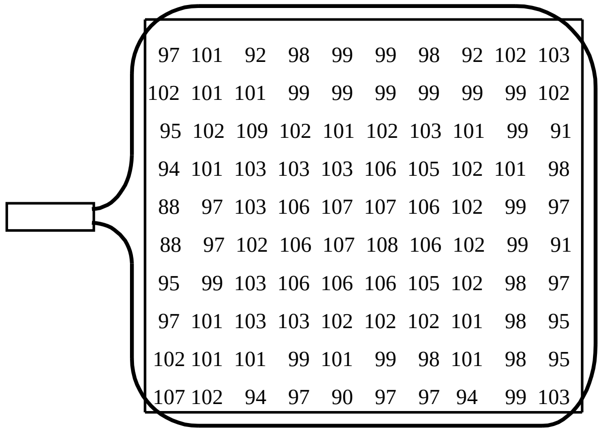
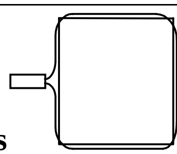
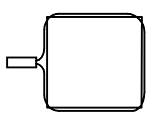
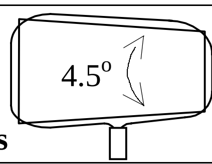
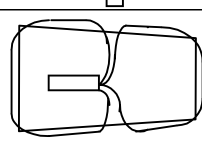
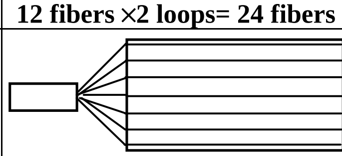


FIGURE 7. Uniformity of light response for counters using WLS fibers. Measurements used the radioactive source Ru^{106}. Counter 4, 200×200×3.3 mm^3, σ_I/I=4.2%, I_{max}/I_{min}=1.21.

TABLE 3. Test results of counters using to side oriented WLS fibers.

Coun-ter #	Design	Sizes, mm^3 Scintillator	N_{phe} on center	Non-unifor-mity	Timing	
					σ_t ns	Δ t ns
11	 **12 fibers**	465×325×12.7 Bicron 404A	54	±3.5%	1.0	1.5
4	 **3 fibers**	200×200 ×3.3 Bicron 404A	17	σ=4.2%	–	–
18	 4.5° **12fibers**	1054×597×12.7 Bicron 404A	37	±7%	1.3-1.9	3.7
18a	 **12 fibers ×2 loops= 24 fibers**	1054×597×12.7 Bicron 404A	52. (43 worst point)	±11%	1.5	3.2
20	 **6 fibers ×7grooves= 42 fibers**	914×318×12.7 Bicron 404A	51	±10% σ=8%	0.8	4.5

that a counter of size 465×324×12.7 mm^3 using only 3 fibers gets 34 photoelectrons and good enough timing with σ_t=1.48 ns. The uniformity of light yield for counter with sizes 200×200×3.3 mm^3 is shown on Fig.7. Note that the variation of the scintillator plate thickness gave noticeable part of the measured non-uniformity for this thin counter. Uniformity for 12.7 mm thick counter 12 is 1.5 times better. It is easy to improve the light yield for counters using so few fibers by a factor of 1.8 by the use of more efficient but more expensive double-clad Kuraray Y-11 fibers [5].

COUNTERS USING WLS FIBERS IN DEEP GROOVES

Design options using fibers in deep grooves are shown in Fig.8. The main idea of this design is the same as using fibers around the scintillator plate: fibers are oriented to collect the light to the smaller sides of scintillator. Fibers for the tested prototype are placed in 1.2 mm wide 6 mm deep grooves with 50 mm spacing between grooves. Fibers are glued into the grooves using epoxy glue on 1cm of their length with 20 cm spacing between the glued points. The ends of the fibers opposite the PMT are glued into the grooves and diamond-cut flash with the scintillator plate. This end of scintillator plate (and fiber ends) are made reflective using aluminized tape. Bicron 404A scintillator and 1mm diameter Bicron BCF92 WLS fibers are used.

Test results for this prototype are shown in Table 3. Direct comparison of the number of photoelectrons versus coordinates for this prototype and for the counter of the same size but using fibers in flat grooves is shown in Fig.9. Counters with flat grooves have 20% more light on average, and 26% more in the center of counter. Both counters have the same light for the worst for light yield point on the corner opposite to PMT. Maximum to minimum ratios are ($N_{phe\ max}$ / $N_{phe\ min}$) =1.61 for flat grooves design and ($N_{phe\ max}$ / $N_{phe\ min}$) =1.16 for the deep grooves case. The uniformity is nearly 3 times better for the prototype with deep groves.

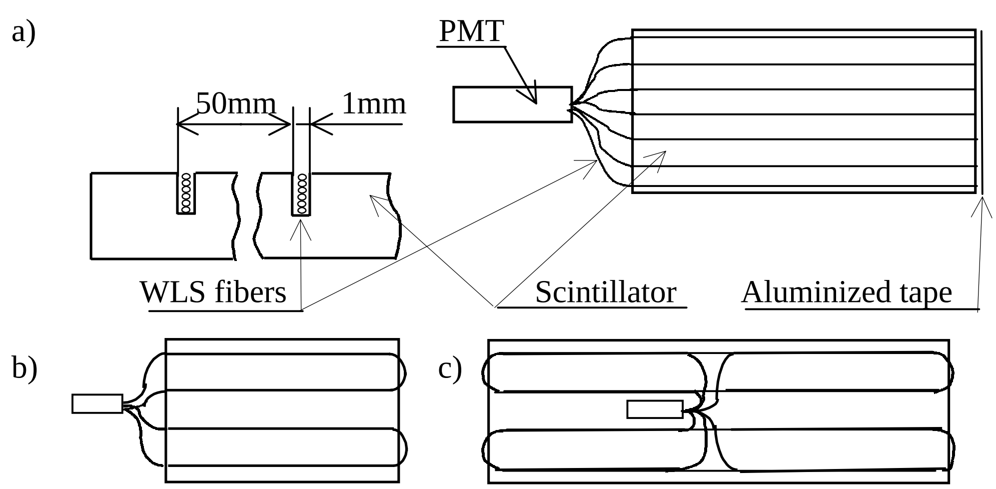


FIGURE 8. Deep grooves design. a) tested prototype; b), c) – design options.

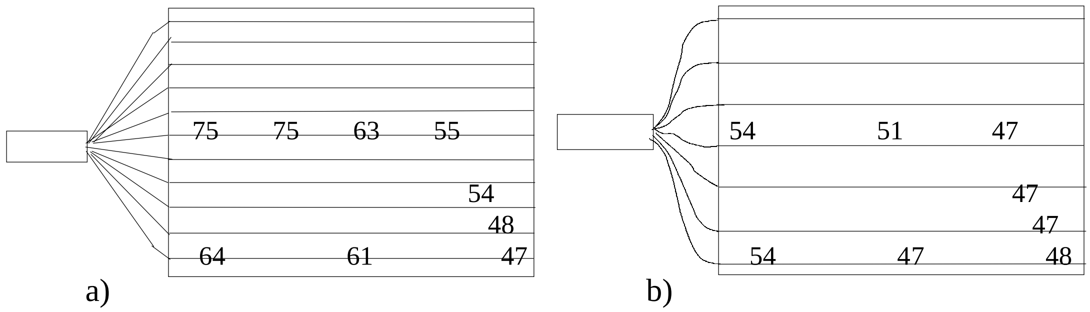


FIGURE 9. Number of photoelectrons versus coordinates using cosmic rays and the same size counters: a) counter 17, flat grooves, 160 fibers; b) counter 20, deep grooves, 42 fibers.

COUNTERS WITH UNPOLISHED SCINTILLATOR PLATE SIDES

The study of counters with unpolished but machined scintillator plate sides was performed in comparison to counters with polished (diamond-cut) plate sides. Namely, the top and bottom sides were polished in both cases but 4 edge sides machined only for this test. The results in tables 1-3 are mainly for the diamond-cut sides of scintillator plate. The result of this study is presented in Fig. 10. Light yield ratios are ($N_{phe\ unpolished}$ / $N_{phe\ polished}$) = 1.07±0.03 for counter 11 and ($N_{phe\ unpolished}$ / $N_{phe\ polished}$) = 1.10±0.05 for counter 14. The same ratio for small counter 13 using 2 bars is 1.03±0.03. Cheaper unpolished variants gave even better results in light yield. Uniformity is the same in both cases for counter using fibers but better for the unpolished variant of counters using bars. Tests with 2 unpolished sides of scintillator for counters using bars also were performed. The variant with all polished sides and the variant with 2 sides of plate opposite to the bars unpolished are consistent within errors. Counters using scintillator with 2 unpolished sides along WLS bars gave better results than the polished variant.

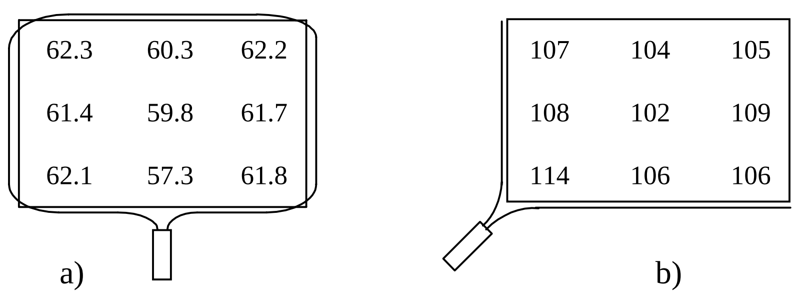


FIGURE 10. Number of photoelectrons versus coordinates for counters with unpolished scintillator plate sides: a) counter 11a, 12 fibers; b) counter 14a, 2 bars.

CONCLUSIONS

1. The efficiency of light collection on the number of photoelectrons, uniformity of response and time resolution have been measured for about 20 prototype counters using several methods of light collection from scintillator using WLS bars and WLS fibers.
2. New variants of light collection from scintillator were tested with good results:
   - The method based on WLS fibers around the perimeter of the scintillator plate gives $N_{phe} = 54$, $\sigma_t = 1$ ns, and the uniformity of $\pm$ 3.5%. This design is good for counters in cramped areas or in a strong magnetic field . It is easy to extend few fibers out of a high field area.
   - Light collection method using WLS fibers placed in deep grooves on the scintillator requires fewer fibers, but showed nearly the same light collection efficiency with better uniformity than the method based on flat grooves.
3. Two designs have been chosen as the basic options for the DØ muon system upgrade:
   - The method using two WLS bars bent at 45° for the forward muon scintillation counters; a few counters for forward muon system in cramped areas will be produced using the design with fibers around the perimeter of counter;
   - The method using WLS fibers in a deep grooves is used as a basic option for central muon scintillation counters.
4. Measurements using a scintillator plate with unpolished (but machined) sides was performed for some of light collection methods. The less expensive unpolished variant is not worse (even better) than the polished one in the yield of photoelectrons and uniformity for the studied methods.

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