BNL Experiment E949
Technical Note K-013

T-counters with WLS fiber readout

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1 Introduction

In this paper we report on the performance of the plastic scintillation counters with wavelength shifting (WLS) readout which were developed to replace the T-counters in the experiment E949.

These counters are installed as the innermost layer of the Range Stack (RS) to produce the trigger signal for DAQ. It was found that the light yield (l.y.) of the original T-counters was degrading over the past several years. Their average light output was only $/sim3$ p.e./MeV for a single end. This effect leads to drop in detection efficiency of charged particles and, correspodently, to the reduced acceptance. The possible reasons are the yellow light guides and the poor contact between light guides and scintillator. Another major contributing factor was the very poor UV transmission of the acryllic used for the inner lightguides. Moreover, the T-counters were installed with an average gap of 4.5 mm, that reduces solid angle efficiency by about 4%.

In contrast to the old T-counters, where scintillation light was read out by acryllic light guides, the new counters are read out with WLS fibers. Such readout allows us to avoid gaps between counters arising during installation in the RS mechanical frame ("spiderweb"). The main requirement of the T-counters is high detection efficiency for MIP while the time resolution is provided by RS counters. High light yield over a whole counter is needed to satisfy this requirement.

2 Fabrication of T-counters

The configuration of a T-counter is shown in Fig. 1. The counter was cut of Bicron BC404 scintillator plate of 7 mm thickness. The plastic profile is trapezoidal with a 7.5^o bevel to pack closely with its neighbours with an average gap of 0.5 mm (compared to 4.5 mm in the old counters). The counter length is 520 mm, largest width is 119.3 mm, smaller width is 117.5 mm. 17 grooves run along the slab with 6.9 mm spacing.

Instead of using a wrapping material for a reflector we applied a novel technique: a scintillator was etched by a chemical agent that resulted in the formation of a micropore deposit over the plastic surface, following which the diffuse film is fixed in a settling tank. The deposit thickness depends on the etching time. An advantage of this approach over the commonly used white diffuse papers is the almost ideal contact of the reflector with the scintillator. It was found impractical to shield the grooves during etching. After etching a scintillator, including the grooves, the white deposit inside the grooves was removed by scraping along the groove profile. Then the groove surface was polished using a thick thread and a polishing compound (tooth paste).

Multi–clad BCF–92 fibers of 1 mm diameter were employed for waveshifting readout. They have a decay time of around 3 ns and the re–emitted light spectral peak at 500 nm (green light). Bicron optical epoxy cement BC-600 was used as an optical couplant between the fibers and a scintillator. Gluing was done in two steps. First, the grooves were filled with the glue and the fibers were inserted. In second step, the glue was applied over the fibers to top up remaining gaps.

Tyvek reflector sheet was put over glued fibers. The assembled counter was wrapped in an aluminum foil for mechanical protection and light isolation. The thickness of all assembled counters was measured to be 7.75 ± 0.25 mm, where 0.75 mm comes from wrapping and the protrusive fibers. Measured thicknesses of all counters are shown in Fig. 2.

17 fibers of 4.8 m length are glued over the counter length. It was found later that the actual number of glued fibers for a few counters is 16, as was specified initially. The fibers are protected from breaking outside the counter with a soft foam plate of 5 mm thick. The short plastic sleeves are put over fibers from the counter edge, and the sleeves are fixed to the foam plate shaped as a trapezium. The fibers then are combined into a bundle inside a black flexible tube. At both ends the bundle is glued into rectangular connectors made of lucite, and finally, the fiber ends have been polished.

General view of T-counters as well as the details of them can be seen at
http://www.phy.bnl.gov/ kmarat/ or
http://www.phy.bnl.gov/e949/detector/tracking/rs/t-counter/e949.html

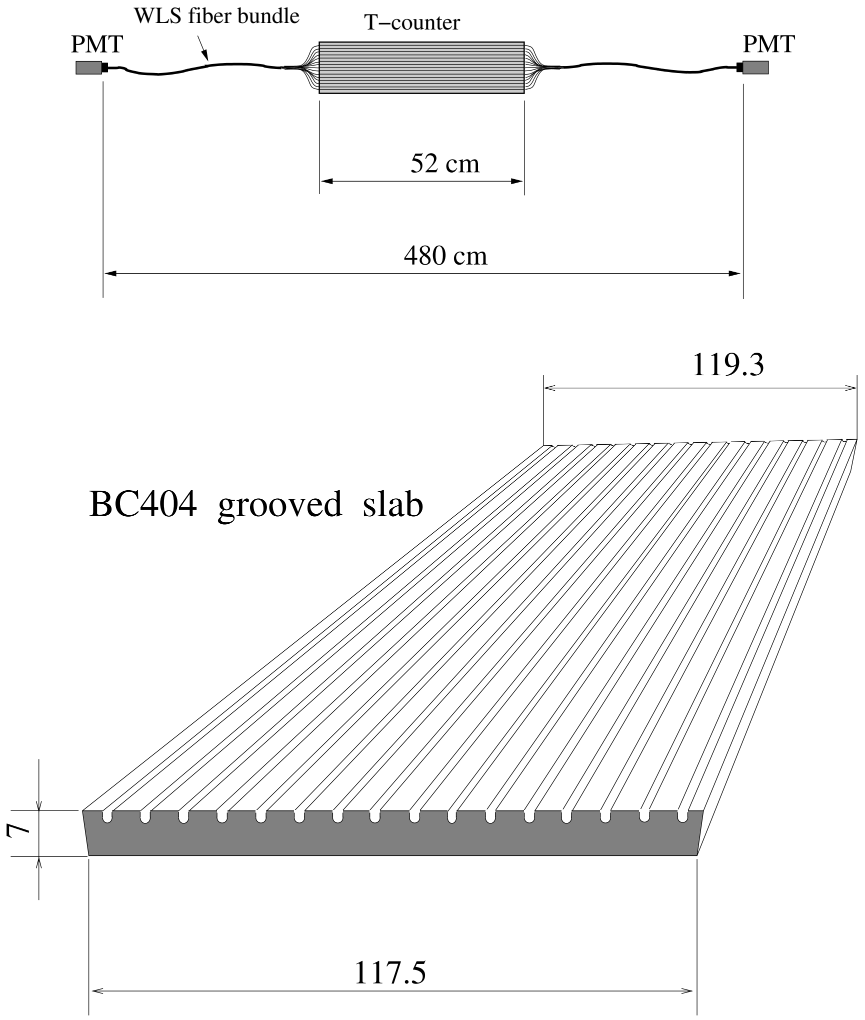

Figure 1: Configuration of T−counter.

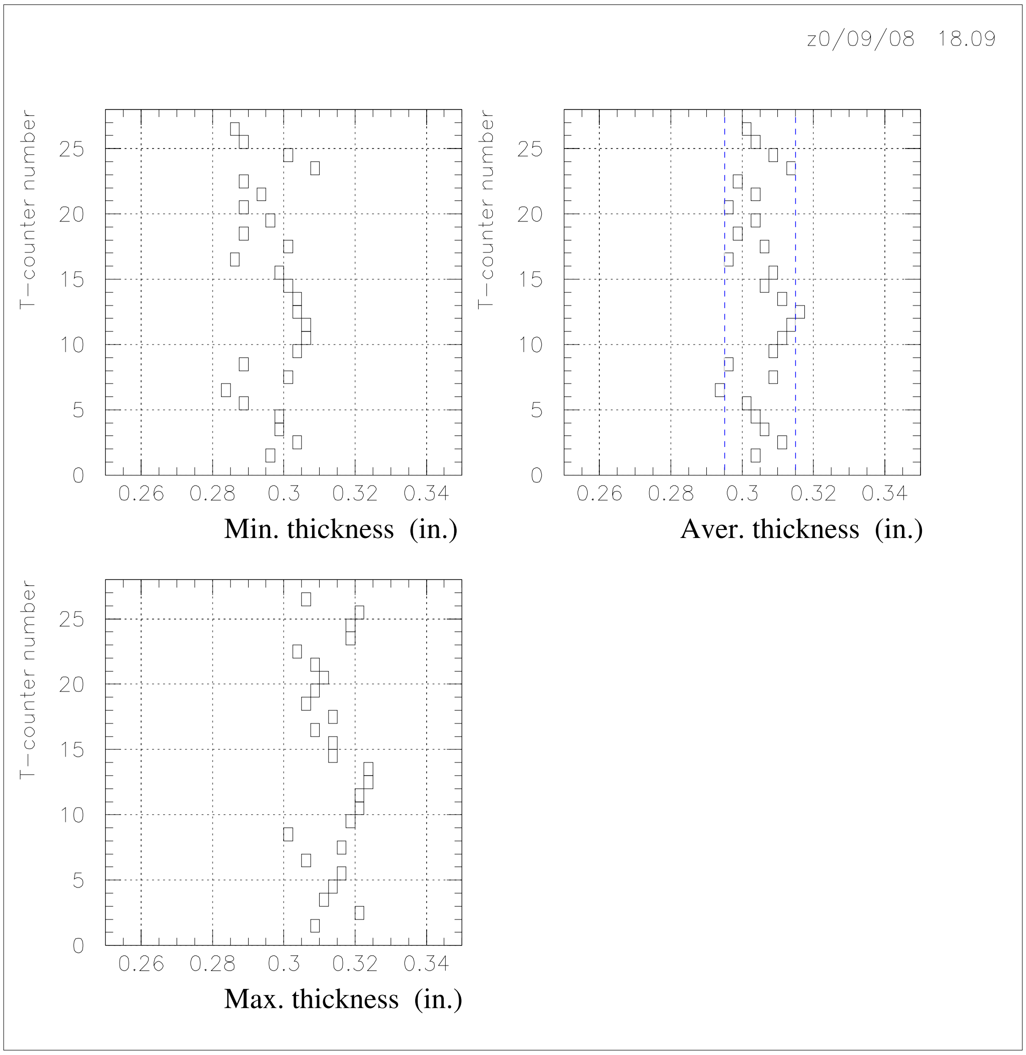

Figure 2: The thicknesses of all assembled counters. The thickness was measured by a micrometer in 6 points along a counter.

3 Photomultipliers

A comparison of different phototubes of similar size was done. The old tubes are Hamamatsu R1398 characterized by a good single photoelectron response (SER). We plan to use russian made tubes FEU-115M which have enhanced sensitivity to green light. First we measured SERs for a couple of tubes of both types. Results are shown in Fig. 3. A ^{241}Am-scintillator pulser was used for the calibration. The intensity of the SER peak was adjusted by the distance between the pulser and PMT face. We made the measurements with average $n_{p.e.}$=1, i.e. with ratio between the pedestal hits and total number of triggers N_{ped}/N_{tot} =0.36. In this case the real SER amplitude will be slightly overestimated, and thus light yield will be underestimated.

Using the coefficients obtained we can estimate the l.y. directly in terms of the number of photoelectrons. Minimum ionization particles (MIP) were produced by an uncollimated ^{106}Ru source positioned on the T-counter. A trigger pulse was generated by a scintillator placed under the T-counter. The light yield for FEU–115M and R1398 tubes is shown in Fig. 4. Measured l.y. for Hamamatsu R1398 tubes is 27.3 p.e./MIP, and for FEU-115M is 33.6 p.e./MIP. To attenuate the ionization fluctuations the differences between the l.y. for both T-counter ends are also plotted. As we can see FEU–115M produce 23% more light than Hamamatsu tubes. Also the relative resolution for FEU–115M is better.

Comparing with Hamamatsu tubes the russian ones delay the output pulse by 2.5 ns. Maximum allowed HV applied is 2200 V. The manufacturer recommends to keep HV below 2000 V to prolong the tube life time which strongly depends on an average anode current. The divider for FEU–115M is depicted in Fig. 5. Since high linearity of the gain is not critical in our case we applied uniform high voltage distribution at the last dynodes. Uniform divider increases the gain by 6 times compared with the standard one. Roughly the SER amplitude of FEU–115M at 1900 V corresponds the one of Hamamatsu R1398 at 1300 V.

FEU–115M were tested for their relative sensitivity to green light. Green LED generated a pulse that was measured by the phototubes. Response of FEU–115M was n_{LED}=(110$\pm$5) p.e., the two tested Hamamatsu tubes produced about 85 p.e. This result is consistent with the l.y. measurements of the T–counters.

SER measurements were done for each FEU–115M tube using an ADC gate width of 120 ns. In such a way we tested the noise performance of the tubes. The tube was considered too noisy if a single photoelectron spectrum did not show a peak, i.e. the spectrum was broadened by the phototube dark current integrated by the 120 ns gate. 3 tubes of 52 were found noisy. They have been replaced by the manufacturer.

4 Performance of T-counters

4.1 Light yield

Light yield (l.y.) of all 26 counters was measured using an uncollimated ^{106}Ru source. The distribution of the total l.y. (both ends summed) is shown in Fig. 6. The worst l.y. (23 p.e.) was obtained with the counters which were manufactured first. They are not planned to be installed in the setup. Probably, the large spread in l.y. is caused by the different quality of groove polishing.

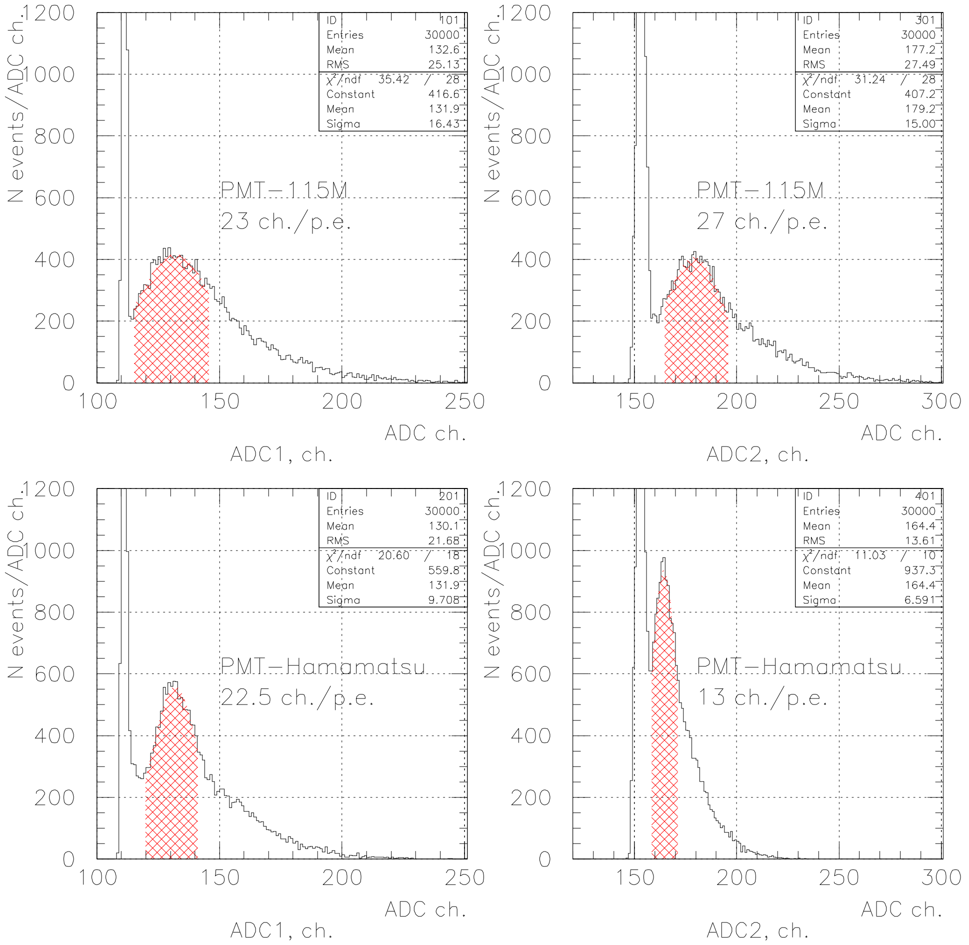

Figure 3: SERs for FEU-115M (upper) and Hamamatsu R1398 phototubes (bottom).

The uniformity of l.y. across fibers was measured for one counter with the collimated ^{106}Ru source. Collimator size was 2x2 mm^2. Scanning was done with 2 mm step over 40 mm length starting at 20 mm from the edge in the central part of a counter. Starting point had been chosen to avoid the edge effect in the light collection efficiency. At least 5 fibers are crossed in the scanned path. As we can see in Fig. 7 no systematic dependence observed, i.e. fiber position does not affect the light output.

The uniformity of l.y. along fibers was measured for a few counters in 3 points: the center and at 2 cm distance from the ends. The total l.y. (sum of both ends) is constant with an accuracy of 5% from average.

To check the intensity change of transmitted light due to a fiber bend, the loops of 10 cm diameter were made at both ends of a fiber bundle. The loops produced no l.y. change. We did not investigate the loops of smaller diameter because of a bundle relative rigidity.

During tests the optical contact between PMT and fibers was provided by a grease.

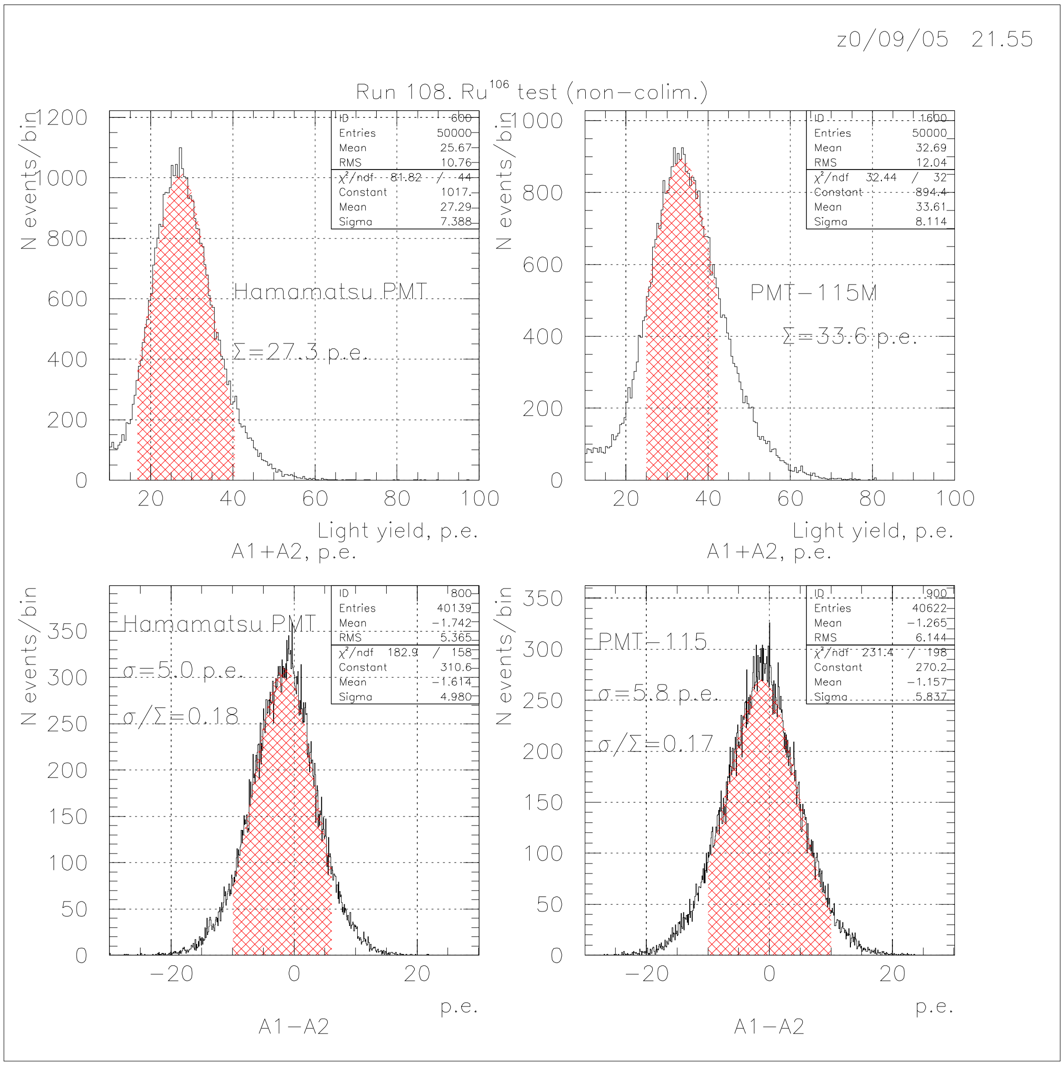

Figure 4: Upper spectra show distributions of the summed light yield for both ends of a T-counter with Hamamatsu R1398 and FEU-115M tubes. Bottom spectra show the difference between the ends. FEU–115M produces larger l.y. than Hamamatsu tubes and demonstrates better relative resolution.

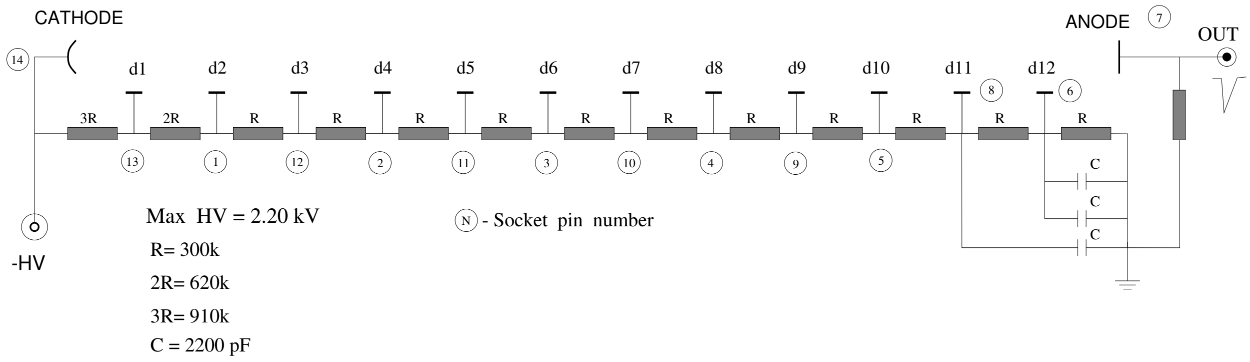

Figure 5: Sheme of the divider for FEU-115M.

Using a silicone cookie as an couplant leads to a slight l.y. drop of 3%.

The attenuation length of WLS readout was measured at both ends. An uncollimated ^{106}Ru source was moved along a T–counter central axis over 48 cm length. The obtained l.y. was changing as shown in Fig. 8. The curves were fitted with an exponential function to deduce the attenuation length L_{att}. We found that L_{att}=2.4 m for the left end, and L_{att}=3.9 m for the right end. The second attenuation measurement with a collimated ^{106}Ru source produced the similar result: L_{att}=2.4 m for the left end, and L_{att}=4.2 m for the right end. Supposing the fiber light transmission isotropy in both directions the explanation for the attenuation asymmetry is a slight l.y. nonuniformity (see Fig. 9) along a counter which leads to large errors in the fitting coefficients. The reason of the light yield gradient is not clear.

4.2 Detection efficiency

The detection efficiency of a T-counter was measured with cosmic rays.
3 fast counters of 5×5 mm^2 area each provided the reference pulses (triple coincidences). The trigger counters were placed above and below the central part of the T-counter. The coincidence of the reference pulse with the double coincidence between T-counter ends gives the counts generated by cosmic rays in the T-counter. The discriminator threshold for the T-counter was set at the level of 1 p.e. maximum amplitude . The reference and T-counter pulses were counted in the visual scalers. The detection efficiency was measured to be 99.8–99.9%.

Usually the detection inefficiency is evaluated by calculating the probability of zero event in Poisson distribution. Simple Poisson distribution assumption is good enough to estimate the relative performance of a detector but not for the quantitive conclusions. In fact, experimental measurement show a distribution with a large relative variance than that predicted by the simple Poisson model. Because we are dealing with a continuous function in l.y., we must calculate the inefficiency by integrating the distribution (assuming Gaussian) below a threshold limit rather than calculating the probability of a discrete zero event (no p.e.).

From Fig. 4 we see the measured l.y. spectrum, where the average total l.y. is 33.6 p.e., $\sigma^{tot}_{l.y.}$=8.1 p.e. Under the detected event we consider the coincidence between the T-counter ends, so for a single end: l.y.=16.8 p.e., $\sigma_{l.y.}$=5.0 p.e., where $\sigma_{l.y.}$ was extracted taking

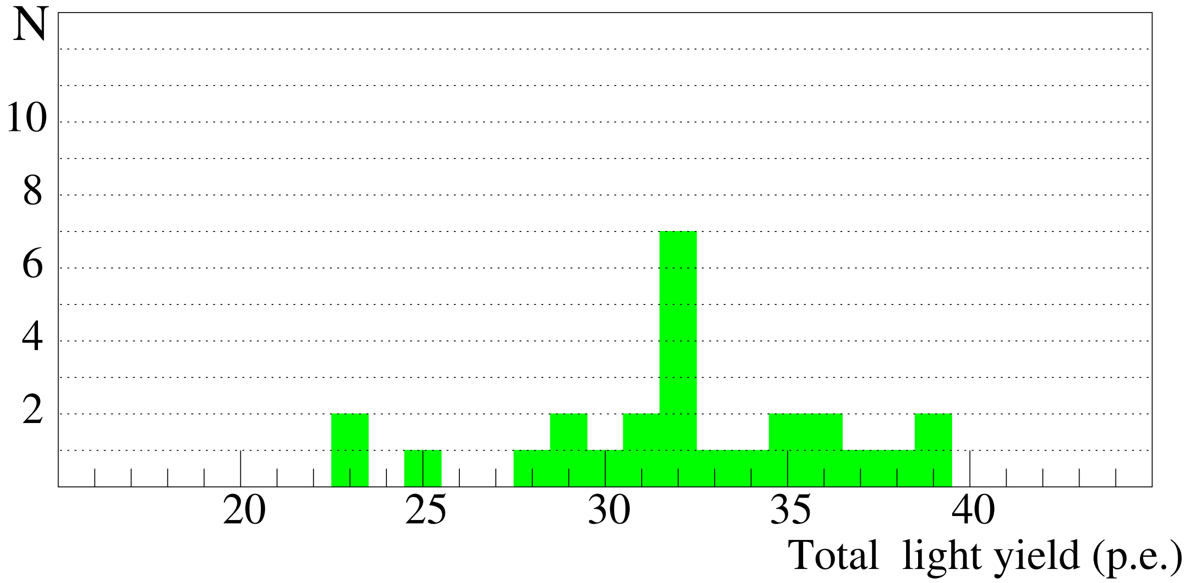

Figure 6: Distribution of the total light yield of 26 T-counters measured with uncollimated ^{106}Ru source. L.y. was measured in the center of the counter. Two counters with l.y. of 23 p.e. are spare.

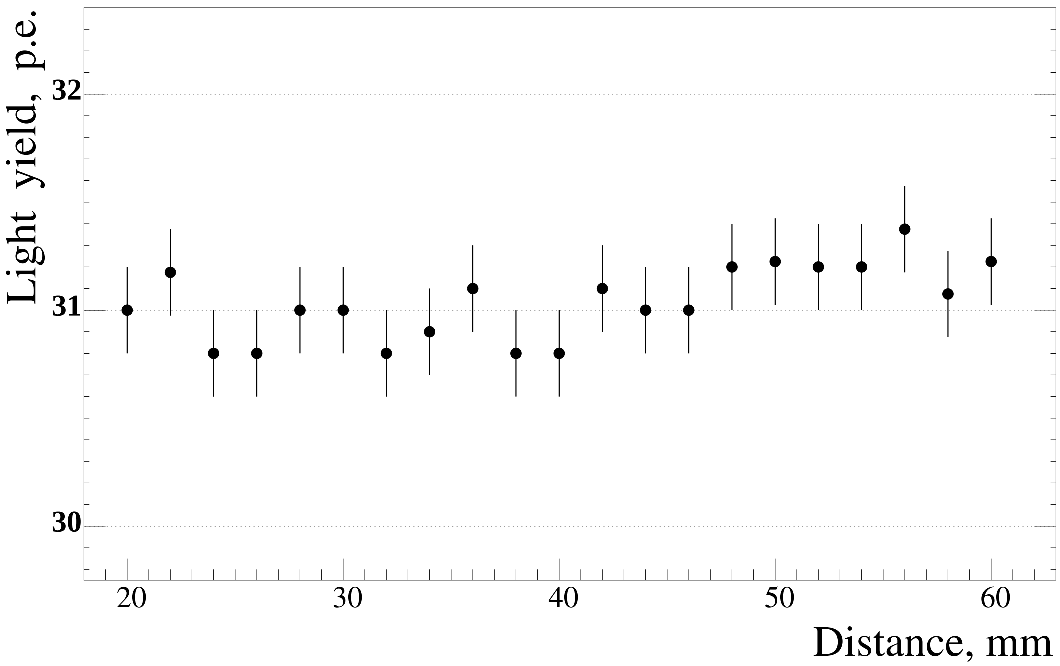

Figure 7: Scan of the total light yield (collimated ^{106}Ru source) across fiber direction. Step is 2 mm, fiber spacing is 7 mm. Collimator size was 2x2 mm^2.

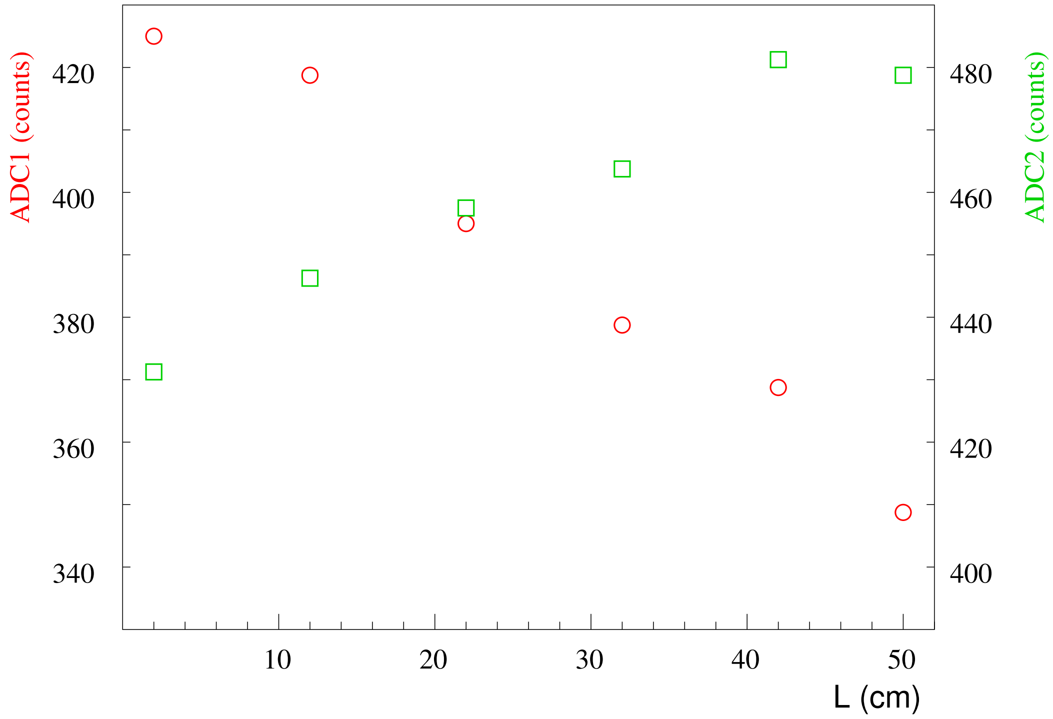

Figure 8: The light yield attenuation along a T−counter at both ends. The circles are a signal measured at the left end (ADC1), and the squares are one at the right end (ADC2).

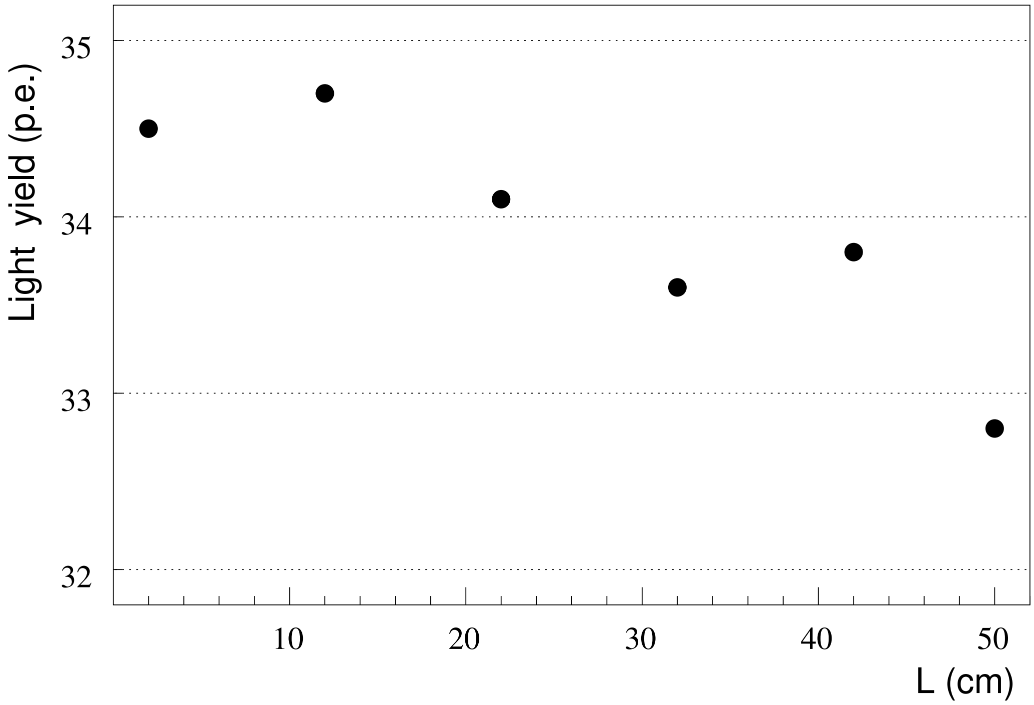

Figure 9: The summed light yield along a T−counter.

into account the correlated (ionization losses) and uncorrelated sources of a variance. These numbers are the parameters of a Gaussian distribution with $\sigma_{l.y.}$=5.0 and the average of 16.8.
Supposing the discriminator threshold is around 0.7 p.e., the probability of l.y.>0.7 p.e. at a T-counter end can be calculated with the special tables. The probability is 0.99936. Hence for a detected event (coincidence between the ends) the probability is 0.99936x0.99936=99.87%, that is consistent with the direct measurement.

In calculation we assume that the measured l.y. is distributed as Gaussian. This simplification allow us to illustrate the fact, that for a high detection efficiency (dominated by photoelectron yield fluctuations) we have to obtain the best relative resolution (l.y./$\sigma_{l.y.}$) rather than a maximum l.y.

4.3 Timing

Constant-fraction discriminators with a threshold set at a level of about 1 p.e. were used to obtain the timing performance of the T-counters. The start was triggered by a fast plastic while the stop signals were produced by the FEU-115M. Then timing was derived from $(t_1 + t_2)/2$ spectrum. A time resolution of 0.65 ns (rms) for cosmic particles was obtained.

Time–amplitude correction is a more accurate method to obtain the good timing. The time resolution of 750 ps was measured using the leading edge discriminators with low threshold (<1 p.e.). Applying the correction in off-line the resolution was obtained to be σ_t=580 ps.

For both methods the contribution from a trigger counter was not subtracted.

5 T-counter installation

The T–counters are attached to the RS modules with an adhesive tape. The fibers are routed through a mechanical channel left instead of an old lightguides to outside the iron end plates. To fit the present RS readout configuration in length a fiber bundle is bent inside the RS lightguides section. The fiber connectors are mounted in a support cylinder (holder) shown in Fig. 10 which is mechanically attached to the "saw" frame. The PMT are coupled with a holder using the old accessories (cookies, magnetic shields, springs). By such a way the PMT are placed in the same position as for the old T–counter readout.

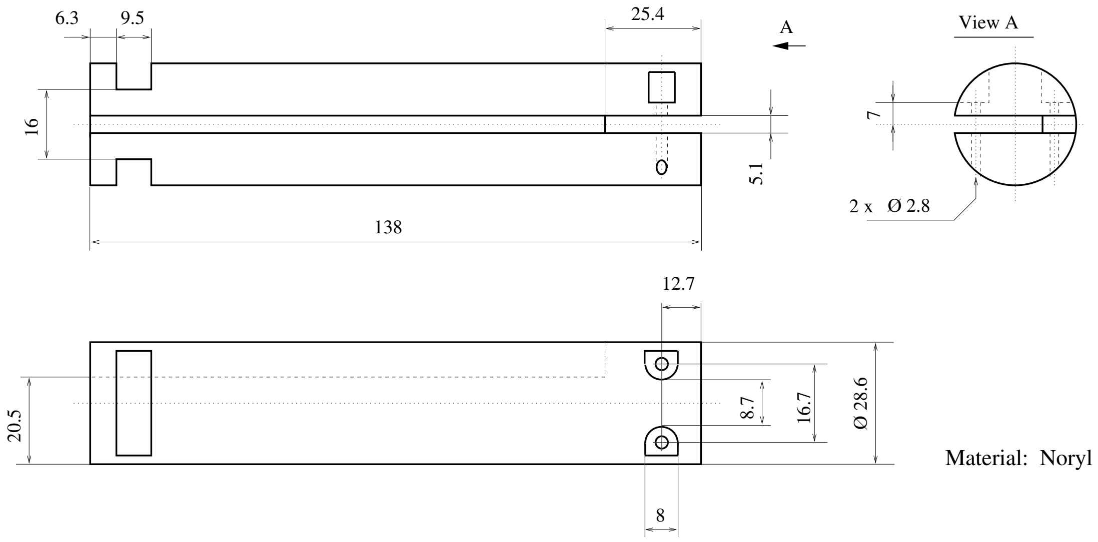

Figure 10: The drawing of the support cylinder (holder).