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Design and construction of new central and forward muon counters for CDF II

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Abstract

New scintillation counters have been designed and constructed for the upgradation of the CDF detector at the Fermilab Tevatron in order to complete the muon coverage of the central detector and to extend it to a larger pseudorapidity interval. A novel light collection technique using wavelength shifting fibers, together with high-quality polystyrene-based scintillator resulted in compact counters with good and stable light collection efficiency over lengths extending up to 320 cm. Their design and construction is described and results of their initial performance are reported.

Keywords: Muon; Scintillation counter; Photoelectron; Amplifier; Optical; Magnetic field; CDF; Photomultiplier

1. Introduction

The importance of detecting muons at CDF and of measuring their momentum accurately can hardly be overstressed. Drell-Yan muon pair production are a mean for testing the basics of the EW theory and for searching additional vector bosons, for leptons and quark substructure as well as for possible extra-dimensions [1]. Muons originate with large branching fractions from the decay of the top quark and of beauty-flavored hadrons. Detailed studies of production and decay properties of the top quark are eagerly awaited and can be best performed in the muon decay channels [1]. An extended beauty physics program, ranging from relatively simple lifetime studies to the study of subtle CP-violation effects can be performed on a muon event sample. A search for the light Higgs boson, that is expected to decay predominantly into b-quark pairs, can be made in the muon b-decay channel [1]. Finally, muons are expected to appear as products of the decay chain in most SUSY processes.

A considerable effort was therefore made in the CDF upgrade [1] to increase the muon acceptance. As a result, the refurbished CDF detector that has started a new run of data taking (Run 2) in March 2001, features nearly complete muon coverage up to a pseudorapidity η of ± 1.5.

Over most of the solid angles the muon detector is a sandwich of drift chambers and plastic scintillation counters, which can be used to trigger on penetrating muon tracks to identify their bunch crossing and to signal their trajectory. In particular, the fast response of the scintillation counters is important in associating a muon track with its corresponding bunch crossing.

The complex and compact CDF geometry (see Fig. 1 and Ref. [1]) has required the construction and installation of a large set of counter hodoscopes employing a total of about 1200 plastic scintillators with different dimensions and light collection assemblies. Part of those (more than 600 counters) constructed for the CDF upgrade was designed to overcome the space restrictions and to improve on light collection from long counters.

This paper describes the design and performance of these new counters, which distinguish themselves by their unconventional and compact light collection system.

The overall performance of the muon detector in terms of muon triggering efficiency and of background rejection will be the subject of a future publication.

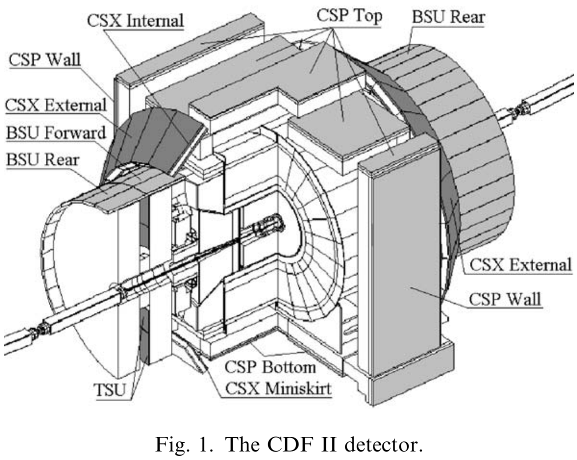

Fig. 1. The CDF II detector.

1.1. Counters for CDF II

Muon momenta are measured in CDF by the central tracker immersed in a solenoid magnetic field (Fig. 2). However, a key signature is obtained from dedicated muon chambers and counters which are placed behind the calorimeter so as to exploit the ability of muon to traverse thick absorbers. Counter areas are large in order to keep the number of individual elements within a manageable limit. Conventional collection systems rely on plexiglass light guides mounted on the counter extremities. These light guides are large and often conflict with other detector parts. Because of this difficulty, the coverage of the Run 1 muon detector was incomplete [1]. Light collection through the counter extremities also involves a large optical path length in the scintillator and is therefore susceptible to deterioration in the scintillator properties. This problem seriously affected the performance of the Run 1 counters [2]. The new counters for Run 2 were designed to overcome any potential performance degrade.

The locations of the CDF II muon detectors are shown in Fig. 1. The coverage of the new system in the $\eta - \varphi$ plane is compared to that of Run 1 in Fig. 3. There are in total about 1200 muon scintillation counters in the CDF II detector. The longest of these counters (320 cm) cover the central region ($|\eta| < 0.6$) and are named central scintillator upgrade (CSP) counters. They are laid on the

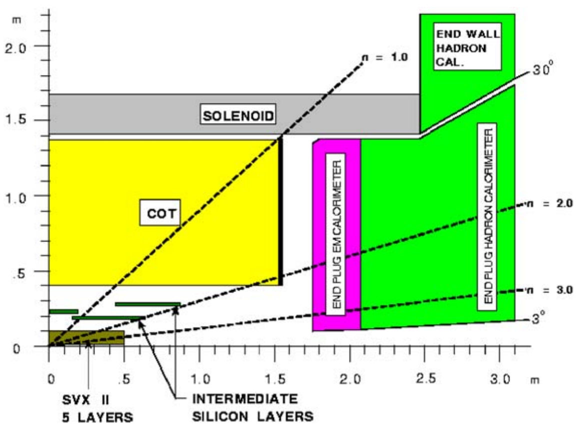

Fig. 2. The CDF II tracking volume.

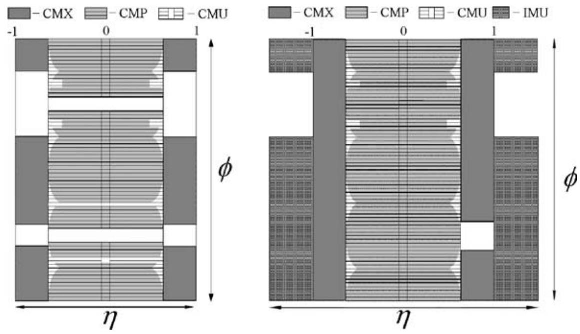

Fig. 3. Comparison of the muon counter coverage in Run 1 (left) and in Run 2 (right), as a function of the azimuth angle ϕ and pseudorapidity η.

outside of the drift chamber of the central muon upgrade (CMP) chamber stacks, behind 61 cm of steel shielding located outside the central calorimeter. The new CSPs cover the top and bottom of the detector (see Fig. 1). The original counters cover the north and south walls.

Because of deterioration of their transmission properties the older scintillators were refurbished [2] by the addition of a light collection system matching the new counter design.

The scintillation counters of the central muon eXtension (CSX) are arranged in a conical hodoscope to cover the region $0.6 < |\eta| < 1.2$. The CSX azimuthal coverage was also completed in the course of the upgrade by the addition of two 90° sectors (the "miniskirts") in the lower parts of both east and west cones [3] and of a 30° sector (the "keystone") in the upper part of the west cone. These counters of conventional design had already been designed and constructed for Run 1, but their installation had been delayed by several obstructions [3]. The light collection system of a subset of them had to be modified according to the new design.

To extend the muon coverage to $|\eta| = 1.5$, two overlapping barrel hodoscopes of 160 cm long scintillators (BSUs) were constructed to cover a barrel of drift chambers (BMUs) that surround the steel of the former toroid magnets (now decommissioned and used for shielding), for about 3/4 of the azimuth (see Figs. 1 and 3). The bottom of the toroid steel is obstructed by its supports. Finally, a pinwheel counter hodoscope (TSU) is located between the toroids and covers the region from $|\eta| \sim 1.2$ to $|\eta| \sim 1.5$. Together with the outer BSU ring, these counters form a projective trigger for the BMU in the region. The TSU counters were constructed at Michigan State University according to a different design [4].

The design, construction and initial performance of the CSP and BSU counters constructed for the CDF upgrade are described below. A major improvement in the construction new counters construction was achieved by employing ribbons of wavelength shifting (WLS) fibers suitably coupled to the sides of the plastic bars for optimal light collection. Bulky light guides were thus avoided and light could be collected more uniformly and more efficiently from the scintillating material. Light collection from plastic scintillators by means of WLS fibers has been adopted in several sandwich calorimeters [5]. This application is different because of its much higher light collection efficiency. In our trigger counters, it was vital to reach full efficiency on traversing minimum ionizing particles (MIP). In calorimeters, the amount of light collected from each scintillator layer is not as critical, since the detector response is the sum of the signals from a large number of layers.

2. The R and D phase

2.1. Merits of the fiber readout

It is customary to collect light from plastic scintillator bars from the short side of the bar with plexiglass light pipes, which are either of a "fish tail" design, or an assembly of suitably bent plexiglass strips. However, since the plastic scintillator bars of the CDF II muon detectors are up to 320 cm long and their transverse dimensions are relatively small ($\leqslant 30$ cm wide and $\leqslant 2$ cm thick), light collection through conventional light pipes in counters of this geometry creates several problems:

- The light transmission efficiency in the scintillator is limited by the non-perfect transparency of the bulk material and by the internal reflection efficiency. In our counters both the optical path length and the number of reflections are large. It follows that the plastic surface must be accurately polished to optimize internal reflection and that the bulk transparency must be extremely good. Furthermore, since the counters will be used for many years, both these properties must be time and radiation resistant. Even a small deterioration of the bulk transparency or of the surface quality leads to a large reduction in the amount of light, which reaches the photomultiplier (PMT).
- For efficient light collection, the area of the PMT photocathode must be as large as that of the scintillator surface which is optically coupled to the light pipe. Since the latter can be as large as 60 cm^2, large and expensive PMTs would be required for optimal light collection. Moreover, large phototubes are particularly sensitive to stray magnetic fields.
- Large light guides and large PMTs occupy a lot of space, and overlaps and conflicts with other detectors can be generated.

These problems were addressed and solved to a large extant by the new CDF counter design, which is based on the use of WLS fibers for light collection. This collection method was used for all new counters with mirror differences, depending on the counter shape. This is schematically shown in Fig. 4.

The merits of this method are:

- Light can be collected from counters of any shape with no concern for possible obstructions by light pipes. It is therefore possible for hodoscopes to obtain complete coverage even in complicated geometries and when one is short of space.
- Since light is collected from the long edge of the scintillator bar, the number of multiple reflections suffered by the light before exiting the edge of the bar is much reduced with respect to conventional light pipes, particularly where the ratio of the transverse to the longitudinal dimensions is small. As a result the tolerance in the quality of bar surface polishing is greatly increased. It also follows that good transparency and light yield of the bulk scintillator become

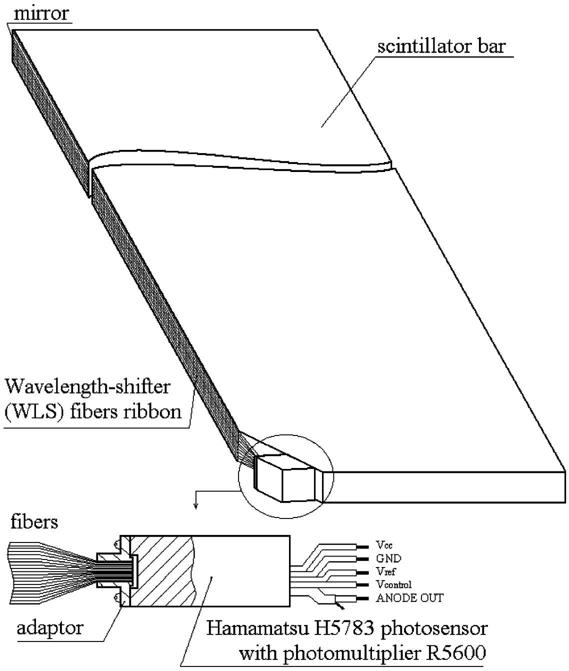

Fig. 4. Scheme of the counter layout employing a WLS fiber light guide.

less critical and that scintillator aging and radiation damage can be better tolerated. The overall result is a more reliable and durable detector.

- One is no longer subject to Liouville's theorem and the total cross-section of the WLS fibers comprising the light–collecting ribbons, which must be optically connected to the PMT photocathodes, is small ($\sim 0.5\,\mathrm{cm}^2$ in our case). Small PMTs can therefore be used and the detector can be made more compact with significant cost saving.
- Small PMTs are less sensitive to magnetic fields. Magnetic shields are often not required or can be much simpler and less expensive.
- The labor costs are greatly reduced with respect to those of light-guide fabrication. When WLS fibers are used one can glue the fiber ribbons to the scintillator and obtain a mechanically solid counter with a relatively simple assembly procedure.
- In some cases, multi-anode PMT can be used to read-out several counters with a corresponding reduction in the cost of the electronic instrumentation.

The design, construction and performances of the scintillation counters subject of this paper are described in the following sections.

2.2. Manufacturing and testing of counter prototypes

A number of prototypes of different shapes and sizes were built [6–10] to test the viability of collecting light by means of WLS fiber ribbons as outlined above and their light yield was measured.

The study addressed the expected performance of counters with geometries corresponding to the BSU, CSP and WSU[3] counters. The BSU prototype was a rectangular scintillator 180 cm long, 17 cm wide and 2 cm thick. The CSP prototype was 300 cm long, 30 cm wide and 2 cm thick. The trapezoidal WSU counter prototype was 180 cm long and 1.5 cm thick with bases of 30 cm and 40 cm lengths.

Counters were wrapped in aluminized paper for diffuse internal light reflectivity and backed by black plastic foil for outside light tightness. An absolute calibration of the PMT (response to single photo–electron (ph.e.)) [11,12] was obtained by flashing the photocathode with a fast light-emitting diode (LED). The response of each counter in terms of ph.e./MIP was measured by using cosmic muons which were selected by a small counter telescope ($4 \times 7\,\mathrm{cm}^2$).

The PMT was joined to the fiber ribbon bundle by optical grease. The other end of the fiber ribbon was blackened in a first set of measurement, then grinded flat with sand paper and a small piece of aluminum foil was applied to it with optical glue. This very simply technique provided a reflectivity of about 60%. The most relevant results of the tests are shown in Fig. 5.

In contrast, for the scintillator the WLS fibers are rather transparent to their own light emission. Therefore, the effective attenuation length in such

[3]The WSU counters were originally intended for the back of the wall calorimeters and were similar to TSU counters, but on the basis of later CDF collaborators considerations they were eventually not built.

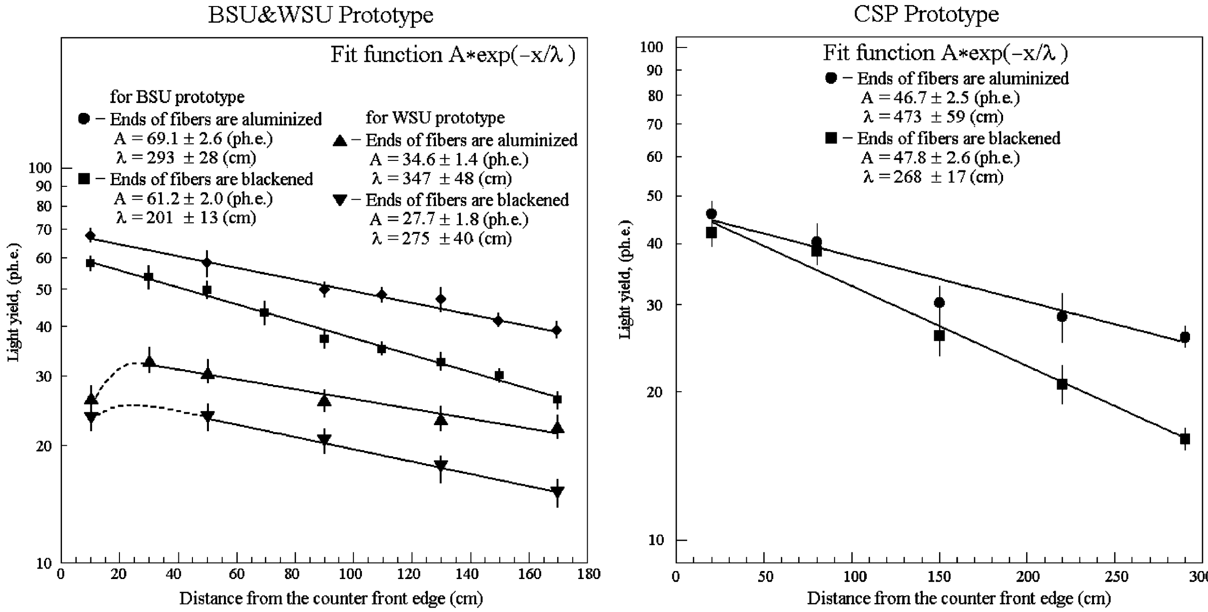

Fig. 5. Test results for the BSU ($180 \times 17 \times 2\,cm^3$), WSU ($180 \times 40\ (30) \times 1.5\,cm^3$) and CSP ($300 \times 30 \times 2\,cm^3$) counter prototypes. The light yield as a function of the distance to PMT.

counters basically depends on the fiber transparency. The scintillator transparency is of lower importance.

The effective light attenuation of the WSU prototype ($\lambda \approx 350\,cm$) is larger than the for the BSU prototype ($\lambda \approx 290\,cm$) due to the configuration of the bars that causes a larger absorption of scintillating light in the WSU counter.

The dopant Y11 [13] features partial overlap of the emission and absorption spectra. The reabsorption effect shifts the emission spectrum to the long wavelength region, where the absorption is less significant while photons are propagating in the fibers. The partial reabsorption process increases the effective attenuation length in long counters relative to shorter ones. Therefore, the effective attenuation length in the CSP prototype ($\lambda \approx 470\,cm$) is larger than in the BSU counter ($\lambda \approx 290\,cm$).

3. Scintillation counters mass production

The scintillator type that was eventually chosen is the UPS 923A of Ukrainian fabrication. It was produced during 1997–2000 at the Institute of Scintillating Materials in Kharkiv, under the supervision of JINR Dubna personnel. The bulk material is polystyrene doped with 2% PTP and 0.03% POPOP. The light yield of this scintillator measured in 1992 at the Pisa INFN laboratory [14] was found to be higher by ~25% with respect to another commercial scintillator (NE 110) produced at that time. Since then, new production techniques were implemented in 1992 at Kharkiv for polymerizing and machining plastic into long bars [15]. The surface machining technique was also replaced by a new one.

After cutting, bar sides were accurately polished until a very smooth surface was reached. The overall light yield from the counter far end (defined as a number of ph.e. emitted from the cathode when the counter is traversed perpendicularly by a MIP) was appreciably improved (Fig. 6).

3.1. Final counter design

The dimensions of the CSP and BSU counters are listed in Table 1. Three different types of CSP

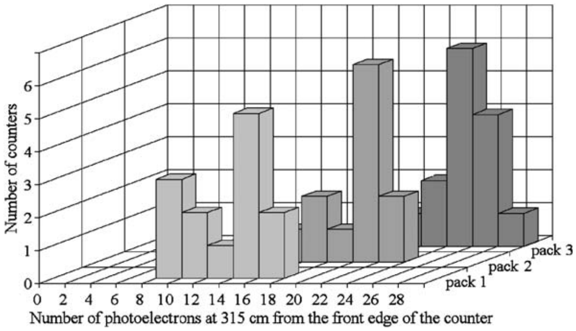

Fig. 6. Dependence of the light yield from the far end (in ph.e.) of CSP L3 counters from different Kharkiv scintillator lots. The scintillator bars quality improved by about a factor of 2 from lot #1 to 3. However, the light yield was in all cases good enough for our purposes.

counters are needed to cover the different parts of the central detector with different space restrictions. Long counters (CSP) are 2 cm thick. The BSU bars, whose length does not exceed 163.8 cm, are 1.5 cm thick. Prototype tests showed that this is sufficient to ensure efficient counter performance. A typical BSU attenuation curve is presented in Fig. 7.

A small notch is machined on one corner of the scintillator bars to house the PMT (Fig. 4). The area occupied by the notch is only a few tenth of a percent of the total scintillator area, hence causing only a very small reduction in the counter geometrical acceptance. Flat WLS ribbons for light collection, are made by gluing 15 or 20 (depending on counter thickness) 0.1 cm diameter fibers with optical cement (BC 600) directly on the scintillator bar edge. The fiber ribbon protruding into the notch is shaped into a bundle and the bundle is glued inside an adaptor. The ends protruding from the adaptor are cut flat and the surface is grinded and polished as required for good optical contact with the PMT photocathode. In order to maximize light collection the ribbon ends opposite to the PMT are "mirrored". This is accomplished by grinding the flat ribbon end with sand paper and gluing on it a small mirror (see Section 3.2).

All faces of the scintillator bars—except the one carrying the WLS fiber ribbon—are accurately polished. Strips of aluminum foils are laid on the side opposite to the ribbon to reflect the light back into the scintillator. A light-reflecting aluminum strip is glued by optical glue to the outer side of the WLS ribbon for increased light capture efficiency.

The large area bar faces are covered with "orange skin" aluminum-backed paper for light reflection.

Blue light is emitted by the wavelength-shifter POPOP in the scintillator. This light reaching the fiber ribbon is absorbed by Y11 (K27 formulation) [13] shifter with subsequent emission in the green region of the spectrum (Figs. 8 and 9). The green light propagates by total internal reflection in both directions along the fibers. The mirror located on the far edge reflects the light back towards the PMT greatly increasing the light collection efficiency [6–8].

Table 1
Dimensions of the scintillator bars

Counters	Length (cm)	Wide (cm)	Thick (cm)
CSP L1	240	30.5	2
CSP L2	310	30.5	2
CSP L3	320	30.5	2
BSU	163.8	16.6	1.5

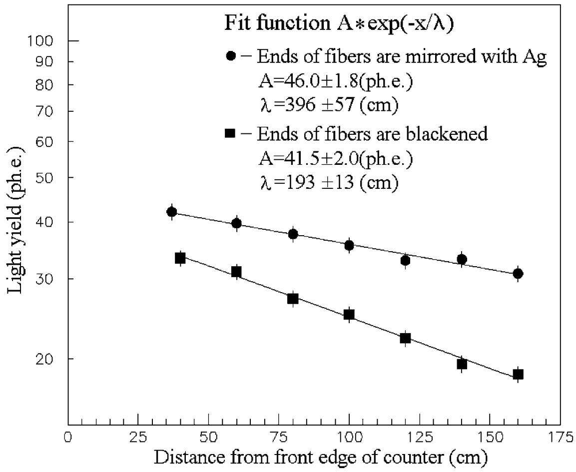

Fig. 7. Measurements of light yield of a BSU counter (15 WLS fibers, KURARAY type).

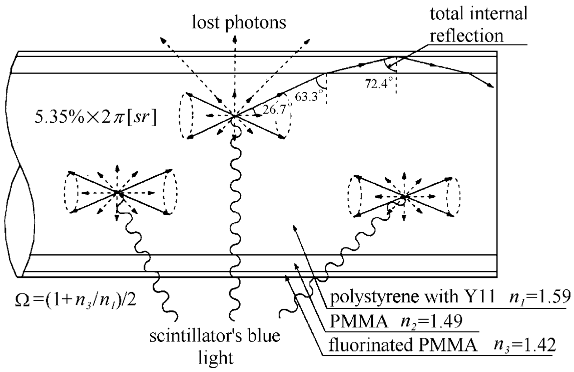

Fig. 8. Principle of the light collection employing WLS fibers.

Multi-clad S-type WLS Y11 (250 ppm) fibers, produced by Kuraray[4], are used for most of the WLS fiber ribbons. The fiber core is polystyrene with Y11 shifter, the inner cladding is polymethil-metacrilate (PMMA) and outer cladding is fluorinated PMMA (Fig. 8). Pol.Hi.Tech[5] (Italy) K27 (200 ppm) fibers were produced in several different lots.

Samples of each lot (for Pol.Hi.Tech fibers) were quality controlled at the University of Rome. Fibers were excited at different distances from the PMT by light from LED. The LED spectra peaks at 450 nm and its intensity were varied adjusting the LED voltage. During each measurement the LED current was monitored. The 3.3 m long fiber was mounted on an aluminum bar and the LED shifted on the bar by a small trolley. For each fiber at least seven measurements between 50 and 300 cm were taken, the points fit by single exponential function. Average attenuation lengths for samples from each lot are shown in Fig. 10. The average attenuation length of the Kuraray fibers Y11 are seen to be ~20% longer than that of Pol.Hi.Tech fibers K27. Pol.Hi.Tech fibers were used for about 30% of the BSU counters to reduce cost.

It should be noted that the light capture efficiency in multi-clad fibers (~5.35%, Fig. 8) is significantly higher than that of single-clad fibers (~3.14%). This factor is essential in bringing the

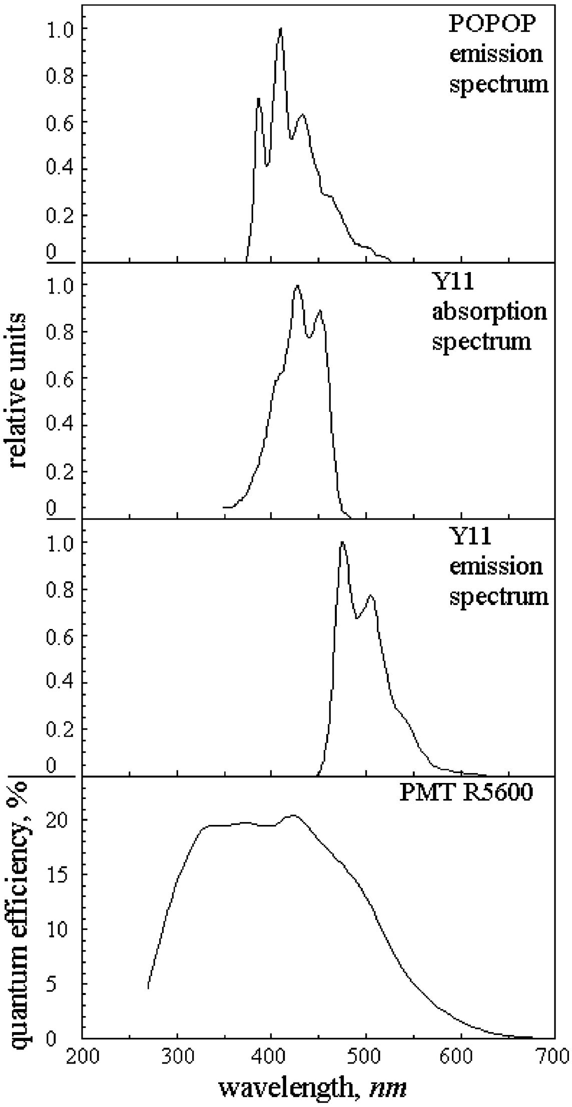

Fig. 9. POPOP emission spectrum, fluorescence converter Y11 (K27 formulation), absorption and emission spectra, and PMT R5600 quantum efficiency.

light collection efficiency of WLS fibers into the range, which made them useful for the application described here.

The 2.2 cm wide, 2.2 cm high and 6 cm long H5783 photosensor manufactured by Hamamatsu Photonics[6], which incorporated the 1.5 cm wide,

[4]Kuraray CO., LTD, Japan, http://www.kuraray.co.jp/en/

[5]Pol.Hi.Tech. company, Italy, http://village.flashnet.it/users/polhitec/

[6]Hamamatsu Photonics K.K., Japan, http://www.hamamatsu.com/

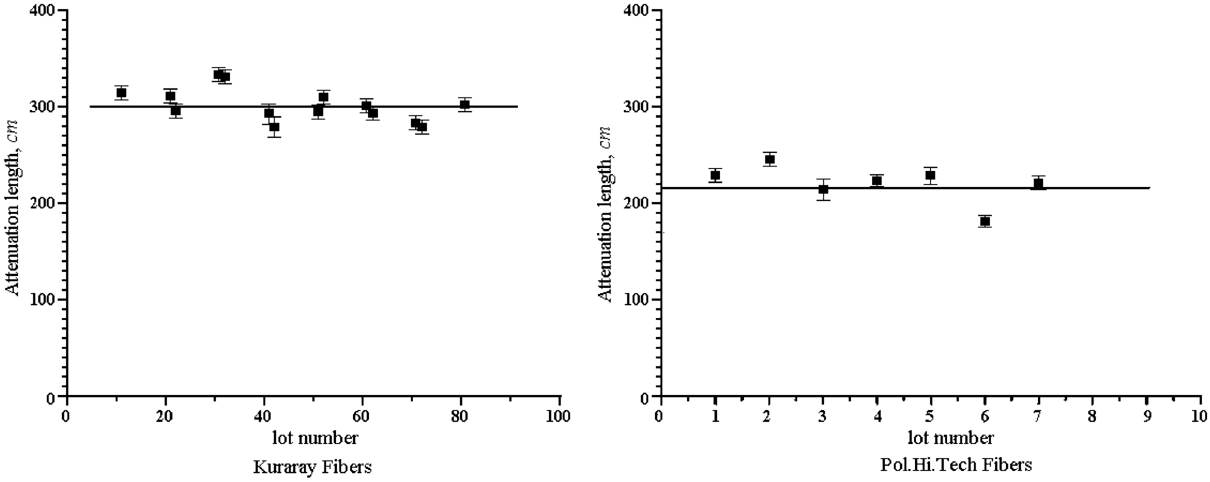

Fig. 10. The average attenuation length of Kuraray and Pol.Hi.Tech fibers as a function of the lot number.

1 cm long R5600 PMT, was used as photon detector. The effective diameter of the photocathode is 0.8 cm and its quantum efficiency is $\approx 12\%$ at the average wavelength of the Y11 (or K27) emission spectrum of $\sim$500 nm.

3.2. Assembly procedure

About 600 muon scintillation counters were built at JINR Dubna for the CDF II CSP and BSU hodoscopes. Although shapes and dimensions were different the same light collection method as shown in Fig. 4 was used for all counters.

The counters were subjected to strict quality controls during production. These included a check of the precision in the mechanical dimensions, the quality of gluing, the quality of surface polishing, the accurate light shielding and, finally, the robust packing for safe shipping.

The importance of a very careful gluing of the fragile WLS fibers warrants a special mention. Air bubbles must be avoided when gluing since they seriously degrade light collection. Only experienced and adequately trained technical staff was employed to perform the work with the required quality.

A custom building-berth was designed and built for gluing the fiber ribbons onto the scintillator bars. This device allowed to safely glue ribbons up to 330 cm long and up to 31 cm wide onto 1.5 or 2 cm thick bars. The building-berth had to be flat and smooth to glue without bubbles the scintillator–ribbon sandwich. For this purpose one usually makes use of massive granite plates with specially machined surfaces. A different, original and considerably less expensive solution was adopted by exploiting the simple property of liquids to settle into a flat horizontal surface under the influence of gravity. The building-berth is shown in Fig. 11. It was assembled in a number of steps. First, the berth support frame was firmly anchored on the lab floor. Next, a solid box was created inside it with plastic walls suitably supported by girders on the perimeter. The box was then filled with epoxy diluted with acetone to increase its fluidity. After the epoxy hardened an excellent flat surface was obtained. The maximum deviation from flatness over 4 m was $< 100\,\mu$m.

A 7 cm wide Teflon strip was fixed with bolts along the full length of the hardened epoxy surface of the building-berth (Fig. 12). A 1.5 and 2 cm wide groove were machined along each strip in such a way that departure from perfect flatness did not exceed 50 μm. In the CSP case, four such building-berths were built allowing up to four “ribbon/bar” or up to eight “ribbon/bar” in the BSU case to be glued onto the scintillator bar each day.

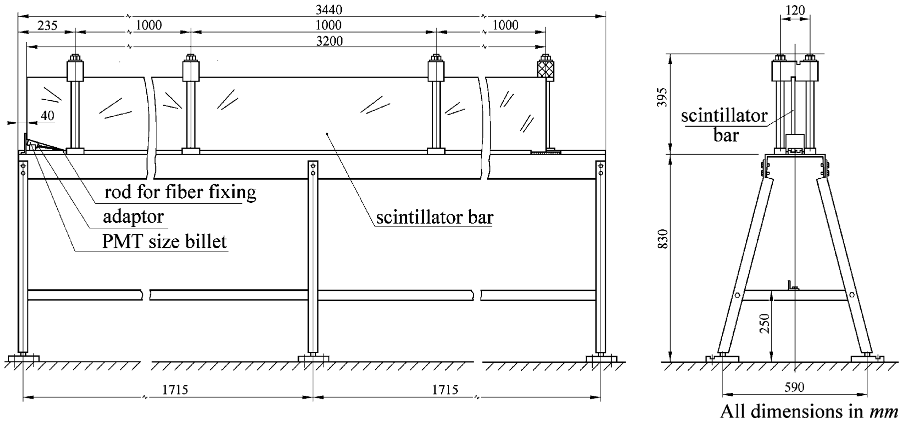

Fig. 11. Scheme of the assembly building-berth. Front and side view.

Counters were manufactured according to the following procedure. First, a strip of aluminum foil was laid in the groove and held in place with scotch tape. Then, the appropriate number (15 or 20) of fibers, which had already been joined on one end and glued into an adaptor, were laid into the groove. The fiber lengths were chosen to be some 5–6 cm longer than the ribbon. The adaptor was housed on the counter with the aid of a billet faking the PMT.

Fibers were carefully stretched out side-by-side to form a flat ribbon in the groove and a temporary rod was used to keep the ribbon in place at the scintillator ends. Finally, BC-600 optical cement was poured into the groove and spread out evenly until it covered the entire surface of the ribbon. By working on such a flat support, the amount of glue needed for gluing a WLS bundle was ~9 g for the BSU and ~21 g for CSP counters.

The scintillator bar was then laid on the ribbon and fixed in position at its top edge by means of a clamp. Then nuts were tightened to ~6–8 N × m (Fig. 12) for providing the optimal pressure. About 24 h were needed for the epoxy to harden. Finally, the scintillator–ribbon sandwich was carefully removed from the building-berth and positioned on a special table for the further work.

The WLS ribbon was cut at its far end, milled, grinded and polished. A "5-min" optical epoxy (Devcon, USA) was used to glue the mirror on this ribbon end. The mirror is a ~0.2 μm thick Ag layer evaporated in vacuum on a plexiglass plate. After about 1 h the plexiglass plate could be removed. As a result the Ag foil remains glued on the fibers. An aluminum foil was glued over the Ag layer as a protection.

The counter surface was then carefully cleaned of the glue spills, fat spots, etc. by wiping it first with a soft cloth moistened with warm water. The operation was repeated with a 50% C_2H_5OH (ethyl-alcohol) solution. Finally, the plastic surfaces were wiped dry.

The counter was then moved by hand to an adjacent table and its large area side was laid on aluminized "orange skin" paper that had been cut to fit the counter shape. The bar edges were covered with aluminum strip so that the counter was fully wrapped in its reflecting coating. Black lightproof ~0.4 mm thick plastic sheets were laid on the two large area sides covering them up to 5–6 mm from the perimeter. The counter perimeter was then covered by black lightproof 50 mm wide electric tape to complete the light isolation of counter. The counter was then ready to be tested with cosmic muons and radioactive sources.

4. Counter performance and quality control

Detector performance studies and quality control checks were performed by means of cosmic muons. The block diagram of the measurement setup is shown in Fig. 13. The analog signal from the PMT is amplified by a high-speed amplifier Model 777 ⟨⟨Phillips Scientific⟩⟩ (~150 MHz band width) and measured by an ADC (Le Croy 2249A). The width of the gate signal is ~80 ns.

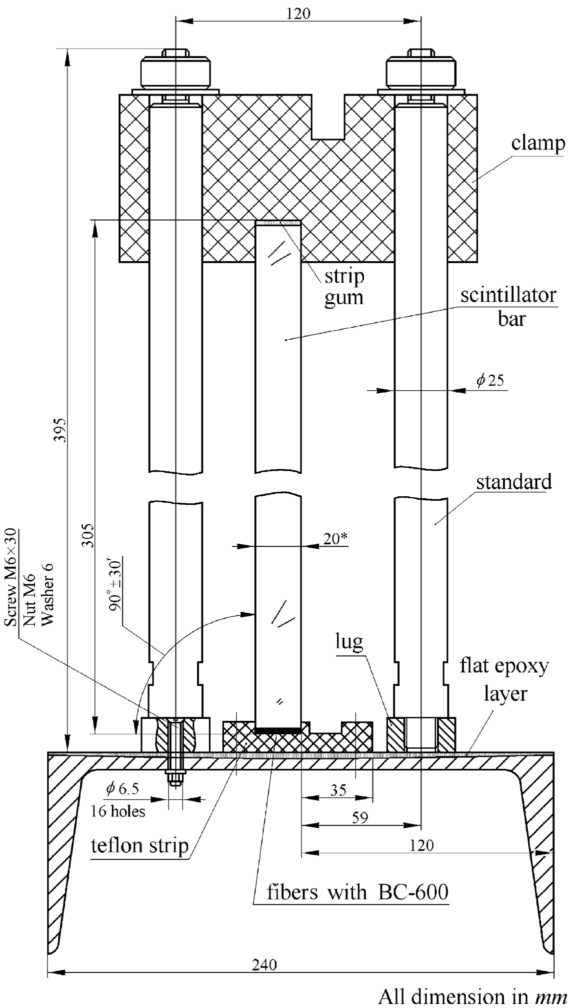

Fig. 12. Technical drawing of the clamping system.

The PMT signal is suitably amplified to obtain a single ph.e. spectrum of amplitude adequate for calibration of a spectrometric channel. An attenuator (ATT) is used to increase the dynamic range of the measured signals. The ADC output is read out and processed by means of a PC. The test setup operates in two regimes with different triggers. Trigger 1 is used to measure the cosmic muon spectra (cosmic muons selected by a telescope of three small $7 \times 7\,\mathrm{cm}^2$ scintillation counters S1, S2, S3 in coincidence) and trigger 2—for calibration of the spectrometric channel.

The counter to be tested is sandwiched between S1 and (S2, S3). Moving the telescope along the counter axis, the dependence of the light yield on the distance from the bar edge is measured. Trigger 2 is provided by a pulse generator and is used for the measurement of the LED spectra. The fast AlGaAs LED HLMP8100 ("Hewlett Packard") is driven by a ~10 ns long pulse. The photon flux incident on the PMT photocathode is tuned by varying the supply voltage of the LED. The LED spectra is used to determine the spectrometric channel parameters and to monitor their overall time drift. For these purpose measurements of LED spectra were carried out before and after each cosmic muon run.

The spectrometric channel is calibrated by measuring the distribution of the number of ph.e. emitted by the PMT photocathode for a traversing muon. The light yield in absolute units characterizes the counter performance. In principle, it would be sufficient if it is at least as large as the one needed to obtain full efficiency, but in

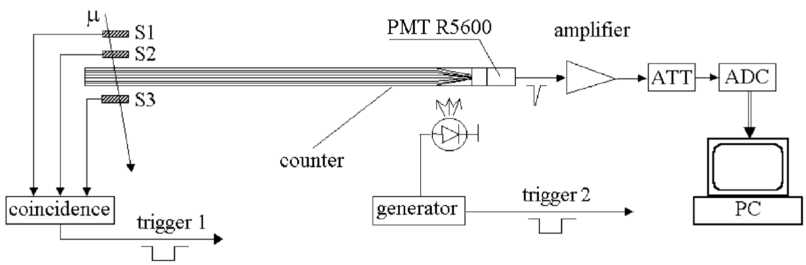

Fig. 13. Block diagram of the setup used for the counters test.

practice, it is important that it is substantially larger to accommodate degradation with time. The knowledge of light yield in absolute units is very important as it enables not only to find the efficiency of the counters and to compare parameters of different detectors, but also to gauge the counters long-term stability [9,10,14].

The calibration is performed by means of a LED using light flashes of low intensity. The basic idea of the method consists in a deconvolution of the LED spectrum with small number of photoelectrons (1–2) by using a realistic PMT response function. A typical deconvoluted LED spectrum is shown in Fig. 14. It corresponds to an average of $\mu = 1.5$ photoelectrons emitted by the PMT photocathode. The solid line shows the PMT response function fitted with parameters as given in figure. The dashed curves represent the charge distribution for ph.e. emitted by the first dynode, since the photocathode is partially transparent. These photoelectrons can be captured by the downstream PMT dynode system. The charge distributions for $n = 1, 2, 3, \ldots$ ph.e. collected by the photocathode are also shown in the figure. The response function has eight parameters, six of them describe the part of the spectrum corresponding to the input light signal:

- $\boldsymbol{Q_0}$, $\boldsymbol{\sigma}_0$—pedestal height and width;
- $\boldsymbol{Q_1}$, $\boldsymbol{\sigma}_1$—mean output charge initiated by a single ph.e. created on the photocathode and the corresponding standard deviation;
- $\boldsymbol{K_1}$—secondary emission coefficient of the first dynode;
- $\boldsymbol{\sigma}_2$—standard deviation output charge when the signal is initiated by a single ph.e. originating from the first dynode;
- $\boldsymbol{\mu}$—mean number of ph.e. emitted by the photocathode and captured by the PMT dynodes;
- $\boldsymbol{\mu}_1$—mean number of ph.e. emitted by the first dynode and captured by the PMT dynodes.

Q_1 given in ADC channels 1 ph.e. gives the spectrometric channel calibration which is needed to measure the counter light yield (in ph.e./MIP). Details of this calibration method can be found in Ref. [16].

Using the calibration constant Q_1, the yield dependence on the longitudinal coordinates was measured with cosmic muons. During this measurement, the dynamic range of the ADC was adjusted by varying an attenuator. About 2 h long runs were needed for each measurement in order to reach the high statistical precision.

The calibration measurements were carried out before and after each cosmic muon run and the

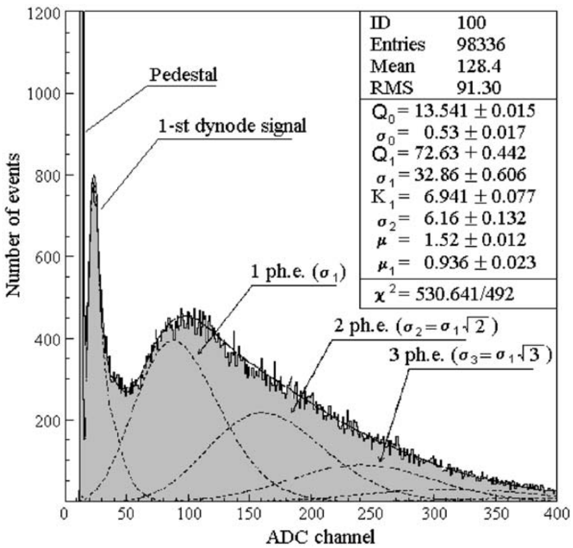

Fig. 14. A typical deconvoluted LED spectrum for the R5600 PMT.

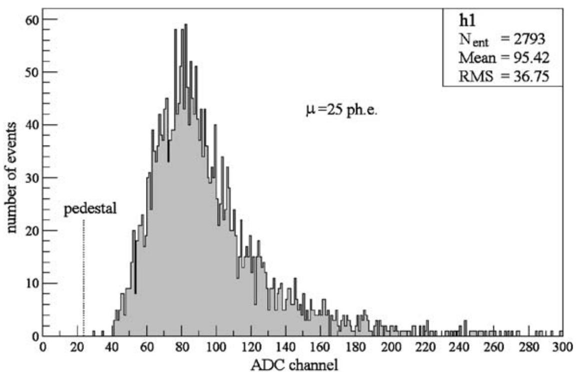

Fig. 15. A typical cosmic muons spectrum taken from the far end of a counter.

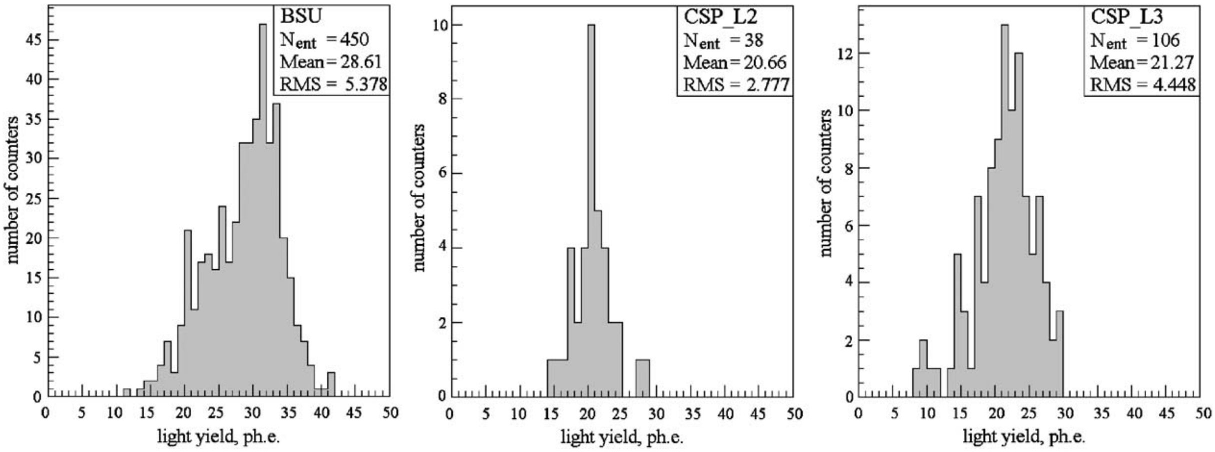

Fig. 16. Distributions of counter light yield from the far end for BSU, 310 cm long CSP L2 and 320 cm long CSP L3 counters, respectively.

calibration coefficient $\langle Q_1 \rangle$ was found as on average of the two Q_1 values [14].

A typical cosmic muon spectrum of a CSP counter is shown in Fig. 15. The dashed line represents the pedestal centroid Q_0. From this spectrum, one finds the average muon signal as

$$N_{\text{ph.e.}} = \frac{\langle Q \rangle - Q_0}{\langle Q_1 \rangle} K_{\text{att}},$$

where $\langle Q \rangle$ is an average spectrum amplitude and K_{att} is the attenuation coefficient.

All BSU and CSP counters were tested as described above. Fig. 16 shows the distribution of photoelectrons over the entire sample for muons traversing close to the far end of the counters.

Note that all tests of counters were made without optical grease between bundle ribbon and face of PMT. Using optical grease the light yield can be increased by $\geqslant 10\%$.

5. Conclusions

A novel technique for collecting light from large area scintillation counters has been developed and successfully applied to the construction of more than 600 counters ranging from 160 to 320 cm in length, to be used for the CDF experiment muon upgrade. The technique relies on a wavelength shifter fiber to extract the light from the longer side of the scintillator bar, thereby reducing the path length of the light in the bulk material and consequently the importance of good light transmission in the counter. Performance of long bars is therefore less dependent on the scintillator transmission properties and less susceptible to its deterioration as compared to conventional light guides.

Another important feature of this technique is the reduced cross-section of the fiber bundle, which allows using smaller area phototubes. The elimination of lucite light guides and of large photomultipliers results in a much more compact design for which the ratio of sensitive to total area is close to one. The reduced sensitivity of small photomultiplies to magnetic fields can also be an important advantage.

The scintillator used to construct the counters (UPS 923A) is a polystyrene-based plastic developed by the Institute of scintillating materials in Kharkiv, under the supervision of JINR Dubna. The counters were constructed at JINR by using a cost-effective technique developed in collaboration with INFN Pisa and engineered at JINR.

The results of quality control tests performed at JINR show that the average ligh output ranges between 21 ph.e./MIP (for the longest counters) and 28 ph.e./MIP (for the shortest ones) for muons traversing the counters transversely at the furthest ends from the photomultipliers. The obtained light collection efficiency is more than adequate for a 100% detection efficiency over the entire counter area. Allowing for a typical deterioration rate of 5–10% per year, full efficiency should be retained more than 10 years and it will be over than useful lifetime of CDF.

Final assembly and quality control of the counters was performed at FNAL. This procedure and the performance of the counters during data taking will be reported on in a forthcoming article.

References

[1] The CDF-II Detector Technical Design Report. The CDF II collaboration, Fermilab-Pub-96/390-E, 1996 (Chapter 10).

[2] S. Cabrera, et al., Nucl. Insr. and Meth. A 453 (2000) 245.

[3] A. Artikov, et al., The Miniskirt counter array at CDF II",—Particles and Nuclei, Letters. (2002) No. 5[114], http://www1.jinr.ru/Pepan_letters/panl_5_2002/03_art.pdf.

[4] C. Bromberg, DPF 2000, Ohio, Published in the Int. J. Mod. Phys. 16 (Suppl. 1C) (2001) 1143.

[5] J. Freeman, et al., The CDF upgrade calorimeter, in: A. Ereditato (Ed.), Proceeding of the Second International Conference on Calorimetry in High-Energy Physics, World Scientific, Singapore, 1993.

[6] J. Budagov, et al., IMU trigger scintillators: BSU prototype results, CDF Note 4210, June 25, 1997.

[7] J. Budagov, et al., CMU trigger scintillators: CSP prototype results, CDF Note 4211, July 1, 1997.

[8] J. Budagov, et al., IMU trigger scintillators: WSU-TSU prototype results and summary of all IMU prototype results, CDF Note 4254, July 14, 1997.

[9] Yu. Budagov, et al., Long scintillation counters with the shift-spectrum fiber light guides, JINR Preprint, Dubna, 1998, P13-93-304 (in Russian).

[10] Yu. Budagov, et al., Test of long scintillating counter prototypes for CDF II, JINR Preprint, Dubna, 2000, E13-2000-127.

[11] S. Tokar, et al., Acta Phys. Univ. Comeniana 40 (1999) 114.

[12] E.H. Bellamy, et al., Nucl. Instr. and Meth. A 339 (1994) 468.

[13] Kuraray CO., LTD, Methacrylic Resin Division, Scintillation Materials, http://www.kuraray.co.jp/en/, e-mail: psf@kuraray.co.jp.

[14] E.H. Bellamy, et al., Nucl. Instr. and Meth. A 343 (1994) 484.

[15] V.G. Senchyshin, Polystyrene scintillators for high-energy physics, Doctor of Technical Sciences Thesis, Kharkiv, 2001. p. 30.

[16] I. Chirikov-Zorin, et al., Nucl. Instr. and Meth. A 456 (2001) 310.