The "miniskirt" counter array at CDF-II

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Abstract

As a part of the CDF Upgrade for Run-II of the Tevatron collider, the azimuthal coverage of the muon detectors between pseudorapidities of 0.6 and 1.2 was completed by the insertion of stacks of drift chambers and scintillation counters, which came to be known as the "miniskirts" because they cover lower $90^\circ$ in azimuth.

The design and construction of the miniskirts was rather complex and posed special problems because of its interference with the floor and the supports of the central detector. The original design parameters of the "miniskirt" scintillator counters for the CDF Muon System are presented and the modifications, testing and installation of these counters in the course of the CDF Upgrade Project are described in detail.
1 Introduction

Muon detection is of prime importance for many of the most interesting physics studies at CDF. In the course of Run-II, the collaboration expects to collect hundreds of $t\bar{t}$ decays yielding a muon as well as several million B-hadron events involving $J/\Psi \rightarrow \mu^+\mu^-$ decays. Muon detection is also of fundamental importance in the study of $W$-boson properties and in the search for Higgs production associated with $W$- or $Z$-bosons [1]. Considerable effort therefore went into extending the muon detector coverage for Run-II, which started in March 2001.

The CDF-II muon detector system consists of multiple layers of drift chambers and scintillation counters, which cover the range of pseudorapidities ($|\eta|$) between 0 and 1.5. Detectors spanning different ranges have different geometries and the muon scintillation counter system includes subsystems in the regions, which have come to be known as the “central” ($0 < |\eta| < 0.6$), “extended” ($0.6 < |\eta| < 1.2$) and “intermediate” ($1.2 < |\eta| < 1.5$) regions of the detector. During Run-I, the “extended” region (referred to by the acronym CMX) covered only three quarters of the azimuthal acceptance with 8 layers of drift tubes sandwiched between two layers of scintillation counters (known as the CSX) [2]. Though much of the missing 90$^\circ$ of the azimuthal coverage, on both the east and west sides of the detector, were constructed before Run-I, installation was delayed until the “CDF Upgrade” and, at that time, it was found necessary to introduce several modifications to the original design. These subsystems of the CMX came to be known as the “miniskirts” because they covered the lower section of the azimuthal range. The counters (which we refer to collectively as the MSX) of one of these miniskirts are illustrated in Fig. 1.

In this note we recall the original design parameters and describe in detail the modifications, testing and installation of the MSX counters in the course of the CDF Upgrade Project.

2 Design parameters

Like the CSX, the MSX are trapezoidal counters of NE114 scintillator, produced about 10 years ago by Nuclear Enterprises [3]. However, the MSX are 15 mm thick (as opposed to the CSX, which are 20 mm thick) and the scintillator turned out to be of better quality than that used for the CSX and for the central counters (known as the CSPs) in that it has not yet shown any evidence of the premature aging, which has shown up in these latter counters [2, 4]. The dimensions of the CSX and MSX are shown in Fig. 2.

The CSX [2] counters sandwich the drift chambers as shown in Fig. 2a. The “internal” (i.e. those closest to the interaction point) and the “external” counters are read out of opposite sides and fed to meantimers in order to reduce the time variation associated with hit position [2]. Due to space restrictions the MSX cover only one side (that closest to the interaction point) of the miniskirts and the counters are read out of both ends, through curved Lucite light guides coupled to 2” EMI-type [5] photomultipliers (PMTs), as illustrated
in Fig. 2b. However, additional space restrictions, not foreseen in the original design did not allow the Lucite light guides to be installed on one end of four counters (referred to as the MSX′) on each side of each of the two miniskirts (see Fig. 1). Conventional readout was therefore substituted by wavelength-shifter (WLS) fiber readout as illustrated in Fig. 2c. The WLS fibers (1 mm-diameter Y11 (200 ppm) fiber produced by Kuraray) were assembled into 15-fiber ribbons, which were glued (using BC-600 optical cement) to one of the long edges of the scintillators and read out by means of Hamamatsu H5783 photomultiplier assemblies which incorporate new ultra compact photomultiplier R5600. Light collection was augmented by “mirroring” the end of the fibers furthest from the PMT photocathode. “Mirroring” was obtained by evaporating an Aluminium coating on the polished ends of individual fibers. Reflection coefficients ranging between 70% and 90% were obtained in this manner.

This solution was arrived at after preliminary studies of the mean timing resolution. Issues related to time resolution are discussed in section 5.

3 Counter calibrations and performance parameters

Phototubes were “calibrated” by illuminating them with low-level light pulses from a fast blue LED (NICHIA NSPB310A), as illustrated schematically in Fig. 3a. The peak corresponding to the single photoelectron was used to extract the calibration constant $k$ (in channels/photoelectron) corresponding to the specific PMT and ADC combination, according to a procedure similar to that described in [6]. These parameters, as well as the average number of photoelectrons $\mu$ used for the calibration, the HV at which the calibration was performed, and the noise rate at that HV, are listed in Table 1 for a pool of EMI PMTs on hand. Of these, 20 PMTs were selected for low noise, high gain and, for counters with light-guide readout on both sides, similar characteristics. The remaining 50 PMTs were new [5].

After calibration and assembly, the number of photoelectrons $n_{pe}$ at the photocathode, corresponding to the passage of a cosmic muon, which we refer to here as the “counter sensitivity”, were measured for all counters. These were obtained from the ADC measurements of the integrated signals as follows:

$$n_{pe} = \frac{\overline{Q} - Q_o}{k/A},$$

where $\overline{Q}$ is the mean of the ADC output distribution, $Q_o$ is the pedestal, $k$ is the calibration constant (in channels/photoelectron), for the specific PMT and ADC combination and $A$ is the amplification factor necessary for isolating the single photoelectron peak while calibrating.

The characteristics of all MSX counters are listed in Table 2, together with their operating plateau voltages and, in some cases, dark currents at those voltages. Noise rates (not all)
corresponding to 15 mV discriminator settings are also shown for a set of counters. These plateau voltages were obtained on the bench, using cosmic muons prior to installation.

A typical light yield distribution corresponding to cosmic muons is shown in Fig. 3b. On the average, the counter sensitivity is \( \sim 80 \) p.e./muon.

4 Counter assembly

All counters were wrapped with diffuse, 0.005"-thick, aluminized paper reflector and a combination of 0.015"-thick black PVC sheet and 0.007"-thick black electrical tape. Single sheets of the reflector and the black PVC sheet were successively laid on all flat scintillator faces, which were then taped down at the edges so the overall thickness of the wrapping material covering the scintillator was 0.054" except for \( \sim 1/2" \) along the edges where the electric tape overlapped the PVC sheet.

All 2" PMTs were coupled to their light-guides using standard CERN mounting assemblies for the EMI 9814B PMT, and they were surrounded by 0.5 mm-thick mu-metal and 1 cm-thick iron shields. The smaller Hamamatsu tubes were coupled to the polished ends of the fiber ribbons via Lucite adapters and mounted on Lucite extensions of the counters as shown in Fig. 2c. They were then surrounded by an aluminium light shield, which was taped down to the Lucite extension with black electrical tape. All PMTs were air-coupled to their respective light-guides/adapter.

5 Timing considerations

Given the length of the scintillators, which range between \( \sim 160 \) and \( \sim 180 \) cm, and the average speed of light in the scintillator (\( \sim 15 \) cm/ns), the uncertainty in the time at which a muon reaches the counter edge varies between \( \sim 10 \) and \( \sim 12 \) ns. This is comparable to the difference in the time a muon takes to reach the counters from the interaction point and the time a background muon takes to reach the same counters from the beam pipe upstream of the detector, at some point close to the MSX. During Run-I, the background of this type [2] would have overwhelmed the CSX signal had it not been for the introduction of a mean timer (MT) circuit, described in ref. 2, to sharpen the timing and eliminate this type of background. In order to reduce this background, additional shielding (two concentric rings of 18"-thick steel, known as the snout and 24" donut between the beam pipe and the CSX and MSX counters [1]), was introduced as a part of the CDF upgrade, however, the acceptance of the plug calorimeters at low \( P_t \) was also increased, with a corresponding increase of material close to the beam pipe, and additional material in the form of small \( P_t \) calorimeters (known as the miniplugs) has been added upstream of the plug calorimeters. Therefore, we estimated the worst acceptable timing resolution from the MSX to be a standard deviation \( \sigma = 3 \) ns, which was sufficient to extract the signal from the background during Run-I [2].
Mean timing is based on the assumption that the two ends of the detector are symmetrical. Under these conditions, if the time \( t_a \) at which the signal is emitted from the PMT at one end of the detector is \( t + x \), where \( x \) is the distance (in ns) from the muon hit to that end of the detector, then the corresponding time \( t_b \) from the other side of the detector will be \( t + l - x \), where \( l \) is the length (in ns) of the detector. The mean of these times then differs from the hit time \( t \) which fluctuates because of the combined fluctuations in the number of photoelectrons \( (n_{pe}) \) at the PMT photocathodes and in the multiplication factor of the PMTs. If the counter is not symmetrical, a systematic uncertainty can also be expected to contribute to the total uncertainty.

Trapezoidal counters are not symmetrical and the MSX' counters, which are read out through a conventional light guide on the one end and via a WLS fiber ribbon on the other, are much less so. One might therefore expect a significant systematic contribution from this asymmetry to the overall \( \sigma \). Furthermore, because the \( n_{pe} \) for WLS fiber readout is smaller than for conventional readout, we can also expect an increase in the statistical contribution to the overall uncertainty. Our first concern, before adopting this solution, was therefore to ascertain that the mean timing resolution obtained under these conditions was adequate.

5.1 Preliminary Tests

The first tests were performed in a non-destructive manner by leaving the Lucite light guides on both ends of an MSX counter and optically coupling a WLS fiber ribbon to one of the counter’s long edges by means of optical grease. The light guides were read out by means of EMI 9814B PMTs whereas the two ends of the WLS ribbon were read out by Hamamatsu R4125 PMTs (see Fig. 4). By combining different readouts one could investigate how the corresponding asymmetries in the light readout contributed to the mean time resolution. For this investigation, the statistical contribution was reduced by using a relatively high-intensity pulsed (5 ns half-width) U/V laser [7] to illuminate the scintillator at localized positions corresponding to 2 mm-diameter holes in the 0.001” black PVC sheet used to wrap the scintillator (see Fig. 4).

The outputs of each of the four PMTs were discriminated and used to stop TDCs, which had been started by the laser trigger. Sums and differences of pairs of TDCs corresponding to similar readouts are plotted in Fig. 5a as a function of position along the long dimension of the counter. The effective velocity of the light in the scintillator and the WLS fiber were calculated from the differences and found to be 14.6±0.3 cm/ns and 14.5±0.7 cm/ns, respectively. The sums of these outputs correspond to the mean times. Ideally, they should be constant but Fig. 5a shows significant variations. In the case of light guides readout a variation of \( \sim0.5 \) ns is observed between the two ends of the counter. However, the variation is not linear with displacement from one end and it reaches a maximum of \( \sim1 \) ns at \( \sim1/3 \) of the distance from the wider end of the counter. These variations are attributed to a combination of the trapezoidal shape of the counter and of the increase of light acceptance as the light source approaches the light guide. The maximum deviation in the mean times calculated from the two WLS fiber outputs is similar (\( \sim1 \) ns) and it appears, as might
be expected, to be approximately linear with displacement along the counter. Statistical uncertainties are considerably larger in this latter case because of the smaller light collection efficiency.

Systematics related to the displacement of the light source in the direction transverse to the longer dimension, i.e. across the detector were also investigated and found to be negligible in the case of conventional light pipe readout. However, variations of up to 1 ns were observed for the WLS fiber readout.

Variation in the mean times obtained when the outputs from dissimilar readouts are combined, are shown in Fig. 5b. Though statistical uncertainties increase due to the effect of the lower light-collection efficiency of the WLS fiber readout, the systematic variation in the mean times does not increase significantly.

The conclusion drawn from these measurements was that the asymmetric readout method would not significantly influence the overall uncertainty in the mean times. Though the effect on the statistical uncertainty of the lower light collection efficiency from the WLS readout was apparent, these preliminary tests could not provide a realistic evaluation of the statistical uncertainty corresponding to minimally-ionizing particles. Measurements of this uncertainty were made using cosmic muons and obtained $\sigma=2.9\pm0.2$ ns for similar, light guide, readouts (this result is consistent with that reported for the CSX in [2]), and $\sigma=6.3\pm0.5$ ns for dissimilar readouts. Given, however, that we expected to increase the light collection efficiency considerably by “mirroring” and by improved optical coupling, we expected that statistical uncertainties would be reduced to acceptable values when these improvements were introduced. This expectation was borne out by the tests described below.

5.2 Timing measurements on the final version of the MSX’ counters

Timing measurements on the MSX’ counters, constructed according to the final design parameters outlined in section 2, were performed with cosmic muons using a scintillator “telescope” as illustrated schematically in Fig. 6 (a more detailed description of the data acquisition (DAQ) electronics is shown in Fig. 7). Two 15x15x2 cm$^3$ scintillators were located above and below the counter being tested. The coincidence of these scintillators was used to trigger the DAQ and to start the TDCs which were stopped by the counter outputs. The contribution $\sigma_{tr}$ of the trigger counters to the total timing uncertainty was measured to be 1.1 ns. Mean times were calculated by summing the TDC outputs corresponding to the two ends of the detector. They were also measured directly using a LeCroy 624 meantimer. No significant difference was found between calculated and measured mean times.

Measurements were performed at 3 different positions along the counters: the center (referred to as X2), a position (X1), closer to the wider end, at 77 cm from the center, and another position (X3), closer to the narrower end, at 82 cm from the center. The results of these measurements are reported in Table 3, where both the full-width at half-maximum (FWHM) and the standard deviation $\sigma$ of individual times and mean times are tabulated.
together with the mean times $< T >$ for all but the shortest (counter 1) of the MSX' counters. The standard deviation $\sigma$ was corrected for the contribution of the scintillator telescope by subtracting it in quadrature: $\sigma = \sqrt{\sigma_{FWHM}^2 - \sigma_{tr}^2}$. It was noted that values of the standard deviation were generally higher at X3 (the end furthest from the PMT) than at other positions. This might be attributed to the presence of Cherenkov light produced by the passage of the cosmic muons through the light guide, which overlaps this region.

The maximum systematic variations in the mean times $< T >$ are seen to be compatible with those measured during the preliminary tests. In order to evaluate their effect on the overall uncertainty, the following algorithm was adopted:

$$FWHM_{tot} = | < T_{X1} > - < T_{X3} > | + \frac{FWHM_{X1} + FWHM_{X3}}{2},$$

as illustrated in Fig. 8. $\sigma_{tot}$ was then calculated from $FWHM_{tot}$ by dividing by 2.35. From these values (tabulated for each counter in Fig. 8), it is apparent that $\sigma_{tot}$ does not exceed 2.2 ns. This is quite compatible with the requirement that the resolution be sufficient to discriminate against background in conditions similar to those of Run I [2], as outlined in section 5.

### 6 Installation and operation

Teflon guides and steel runners were then installed on each counters so they could be slided into position along steel guides fixed to the corresponding drift chamber assemblies. The disposition of counters, power supply and readout between the collision hall and the CDF electronics room are shown schematically in Fig. 9.

Power is supplied to the EMI-type PMTs by power supplies, known as “Gamma Boxes” [8] (located in the “counting room”), via 40-channel distribution units, known as “Pisa Boxes” [9] (located close to the detector), through RG58 HV cables. The Hamamatsu PMTs received their power from supply and distribution units known as CCUs [10], located close to the detector. All power distribution is controlled and monitored by custom software [11]. This software allows for channel-by-channel control and monitoring, both manually and automatically, on a regularly scheduled basis.

Analog signals from the EMI-type PMTs are routed to LeCroy 4416 discriminators, located in the counting room, through 220 ft RG58 cables. All discriminator thresholds are set to their minimum values (15 mV). Discriminator outputs are split and routed both to meantimer units (located close to the discriminators) and to TDCs (via 40 ft twist and flat cable). Meantimer outputs are also routed to TDCs via the same twist and flat cables.

Presently (fall 2002), only three sections of standard (i.e. light-guide readout on both sides) are presently installed. The remaining (North-West) section and the four wedges with the MSX' counters will probably be installed during a forthcoming shutdown.

An example of regularly monitored “occupancy plots”, recorded by the YMON program, is shown in Fig. 10 for both beam and cosmic data.
References

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

[2] P. Giromini et al. "The Central Muon Extension Scintillators (CSX)". CDF Note 3898 (1996)

[3] Supplied in 1992/93 by Nuclear Enterprises Co. Equivalent scintillator is now produced by Bicron (BC416).

[4] S. Cabrera et al., "Making the Most of Aging Scintillator", Nucl.Instrum.Meth. A453 (2000) 245-248

[5] Original PMTs were EMI 9814B PMTs. These PMTs are now produced by Electron Tubes Inc. (UK). Fifty new PMTs were used for the Miniskirt counters. The remaining 20 were older EMI 9814B PMTs.

[6] E.N. Bellamy et al. "Absolute calibration and monitoring of a spectrometric channel using a photo-multiplier”. Nucl.Instrum.Meth. A339 (1994) 468-476.

[7] LN300 pulsed Nitrogen laser produced by Laser Photonics Inc. It features a spectral output of 337.1 nm, pulse width of 300 ps, energy stability of 5%.

[8] Supplied by Gamma High Voltage Research Inc. (US).

[9] Pisaboxes originally built at University of Pisa. Electrical engineers who originally designed Pisaboxes left and founded CAEN (Costruzioni Apparecchiature Elettroniche Nucleari). Pisaboxes are a very simple idea: use small motors connected to potentiometers to set HV, and control and read back values with a microprocessor (8080 vintage). Communications to the Pisabox was a serial connection daisy-chained via RG-174 from Pisa-box controller CAMAC module ("Pisabox protocol"). This was improved first to CAENet, and then H.S. CAENet, which is used on CAEN 527 HV supplies.

[10] C. Bromberg for the CDF Collaboration, "Gain and Threshold Control of Scintillation Counters in the CDF Muon Upgrade for Run-II”, Int.Journal of Mod.Phys.A Vol.16, Suppl. 1C (2001) 1143-1146.

[11] O. Pukhov et al. "Automatization of the Muon Scintillator System Power Supply at CDF-II”, CDF Note 5949 (2002).