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Calibration of the Scintillation Trigger Detector of the Forward Muon System for the D0 Experiment

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Abstract—A procedure for LED-based calibration of the scintillation trigger detector of the forward muon system for the D0 experiment on the Tevatron collider at the Fermi National Accelerator Laboratory (Batavia, United States) is presented. During its 4-year operation, the deviation in the signal amplitudes averaged over 4214 counters was 4% or less and the variance (σ) of the distribution of these deviations over all counters was 10%. In the same period of time, the signals remained stable in time with an accuracy of 0.23 ns and the variance (σ) of the distribution of these deviations was 0.52 ns. The calibration procedure based on measuring the amplitude response of the detector counters to muons produced by proton–antiproton collisions at the Tevatron collider is also described. The variations in the absolute value of the amplitude responses over a period of 4 years were in the range of +3%…–9%.

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INTRODUCTION

To ensure efficient operation of the muon triggers and a high precision of time-of-flight measurements, it is necessary that scintillation counters provide accurate timing information. A stable amplitude response guarantees a high detection efficiency for muons and a low noise sensitivity. To monitor the stability of the timing signals, the gains of photomultiplier tubes (PMTs), and the performance of the electronic circuits, an LED-based system has been developed for calibrating the 4214-channel scintillation trigger detector of the forward muon system for the D0 experiment at Fermilab.

Calibration of the scintillation counters using muons produced by proton–antiproton collisions at the Tevatron collider during Run II of the D0 experiment, which was started in 2001, is very important for examining stable operation of each counter as a unit, since it implies testing of the stability of the PMT and the electronics, as well as of the scintillator and the wavelength-shifting bars.

A SYSTEM OF SCINTILLATION COUNTERS FOR THE D0 EXPERIMENT

The D0 experiment was proposed in 1983 with the aim of studying proton–antiproton collisions with a 1.8-TeV energy in the center-of-mass-system at the Fermilab Tevatron collider (Batavia, United States). The destination of the D0 muon system was to ensure efficient detection and identification of muons over wide ranges of angles and momenta and have a low background level therewith. Stable and reliable long-term operation and a high radiation hardness under conditions of a high luminosity are also very essential for the muon system. The efficient operation of the setup during Run I (1992–1996) resulted in discovering a top quark [1] and obtaining a number of other important results. After completion of building of a new injector and the ensuing upgrading of the Tevatron, the accelerator resumed its operation in Run II in March of 2001.

The D0 detector was substantially upgraded to take full advantage of the improvements to the Tevatron. The diagram of the upgraded D0 detector is shown in Fig. 1, where the northern and southern halves of the detector are denoted "North" and "South," respectively. In the coordinate system of the D0 detector, axis Z is aligned with the proton beam, while axes X and Y are directed transversely to the beam (to the right of the beam in a horizontal plane and upright, respectively). The origin of the coordinate system is located at the center of the central tracking detector.

The muon system of Run I can be conventionally divided into two subsystems: central and forward. The first of these was composed of proportional drift tubes (PDTs) and three large iron toroidal magnets: central toroid *CF* and two forward toroids *EF*. The other subsystem consisted of several planes of drift tubes and two iron toroids magnetized to 2 T.

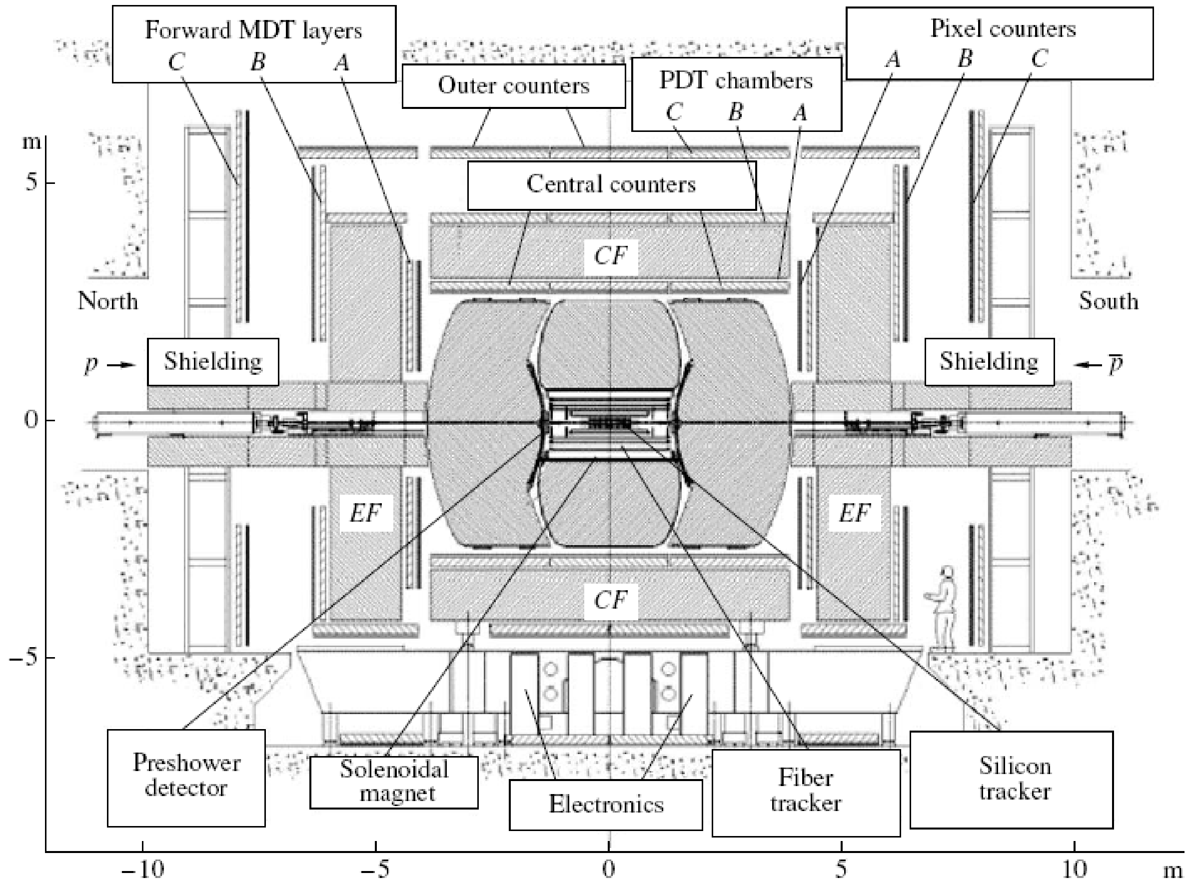

Fig. 1. Schematic diagram of the D0 detector in Run II of the Fermilab Tevatron collider (a side view).

By the beginning of Run II, the PDTs in the region of pseudorapidities $1 < |\eta| < 2$ have been replaced by a new tracking system composed of minidrift tubes (MDTs). A significant improvement to the D0 detector consisted in introducing a new trigger detector based on scintillation counters [2, 3]. All the 4214 counters assembled at the Institute for High Energy Physics (Protvino, Russia) in 1998–1999 were grouped into 48 octants that formed six layers (three layers A, B, and C in both the southern and northern halves of the D0 detector) with eight octants in each. The layers of these counters are denoted in Fig. 1 as pixel counters. Each octant contains 96 counters or less, which are combined into six groups. Each group comprises 16 counters or less and is connected to its own high-voltage source. The division of the layer of counters into octants and the combining of the counters of each octant into groups is illustrated in Fig. 2. The schematic diagram of the scintillation counter is shown in Fig. 3. At both ends of the 12.7-mm-thick Bicron 404A scintillator, there are Kumarin 30 wavelength-shifting bars 4.2 mm thick and 12.7 mm wide. At the edge of two adjacent end surfaces of the scintillator, these strips are bent through 43.9° to transmit light to the ФЭУ-115М PMT 25 mm in diameter. The counter sizes vary widely to fit the configuration of the detector: the smallest counters (9 × 14 cm) are located closer the center of the A layer, while the largest counters (60 × 110 cm) are placed at the periphery of the C layer that is disposed at the maximum distance from the D0 center [4]. Each counter is connected to its own channel of the scintillator front-end (SFE) board. One SFE board has 48 inputs and, therefore, serves one-half of an octant. Apart from the 96 working SFE boards, two supplementary boards were also connected; they were used to perform the calibration procedure with the aid of LEDs.

A PROCEDURE FOR CALIBRATING WITH THE AID OF LIGHT-EMITTING DIODES

The LED-based calibration system [5] illuminates the PMTs by light pulses similar in amplitude and shape to the pulses generated by muons. This system consists of 48 modules, each of which is fixed in place in the plane of the appropriate octant of the scintillation detector.

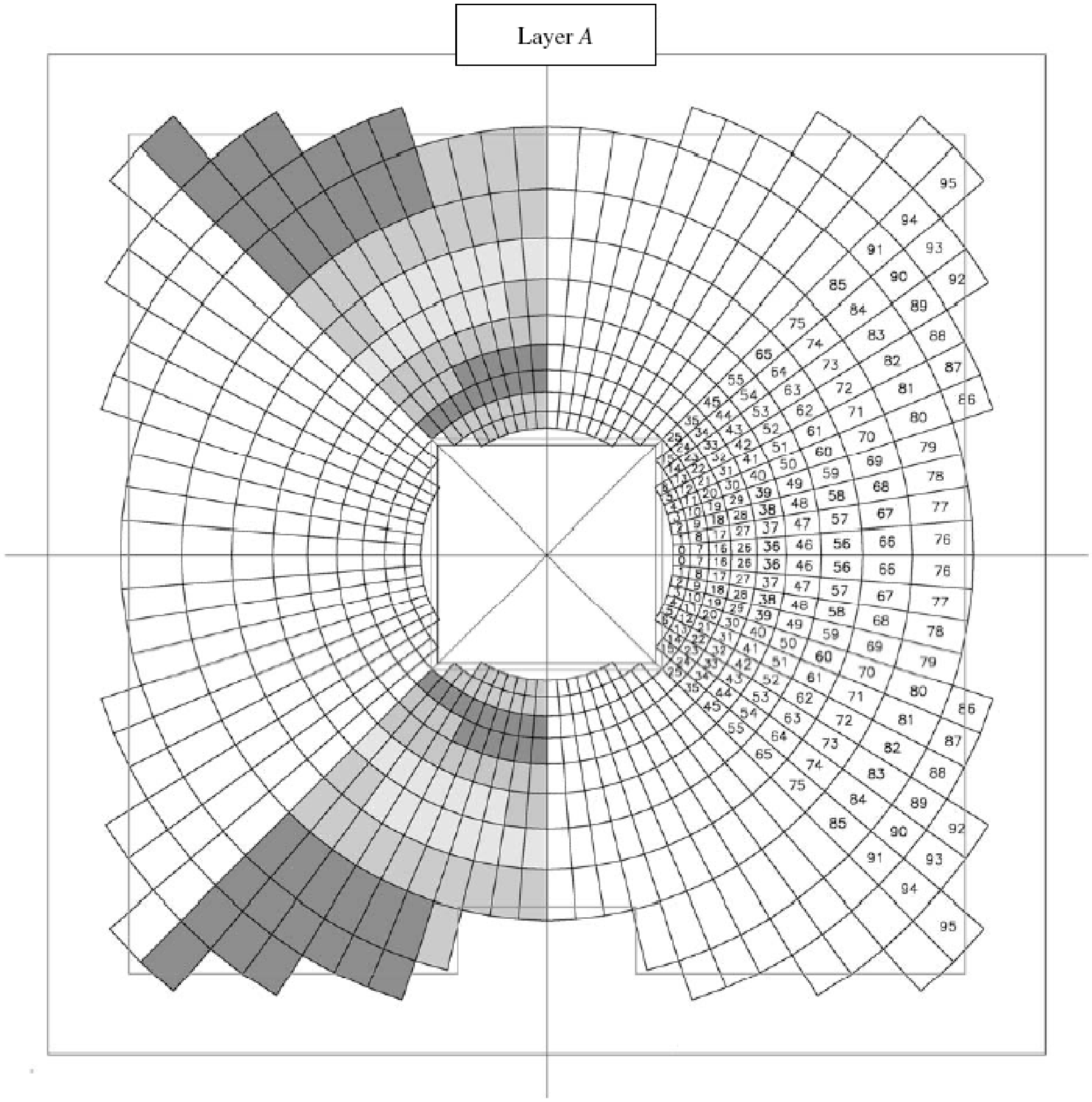

Fig. 2. Schematic diagram of layer *A* of the system of scintillation (pixel) counters. Eight octants are assigned numbers from zero to seven clockwise, beginning from the lower octant of the left upper quarter of the layer.

The module of the LED-based calibration system is schematically shown in Fig. 4. The LED pulser generates current pulses for triggering four LEDs located in the LED block. Blue LEDs of the NSPB320BS type (Nichia America Corp.) are used, since their emission spectrum matches the absorption spectrum of the wavelength-shifting bars used in the scintillation counters.

To ensure uniformity of the emission intensity, the light pulse generated by an LED passes through two light mixing modules. A silicon *p–i–n* S6775 Hamamatsu diode is placed behind the first of these modules to monitor the stability of the LED performance. The second module serves for further mixing of the light via total internal reflection. After passing through the mixing modules, light pulses are split in the fiber module and then transmitted over isolated optical fibers to each of the 96 counters of this octant.

The LED system was used to good effect to test the counters as they were assembled. Now it continues to serve in monitoring the performance of the counters during data acquisition. The LED calibration of the counters is performed approximately once a year in order to check the stability of their performance. This procedure was carried out for the first time in May

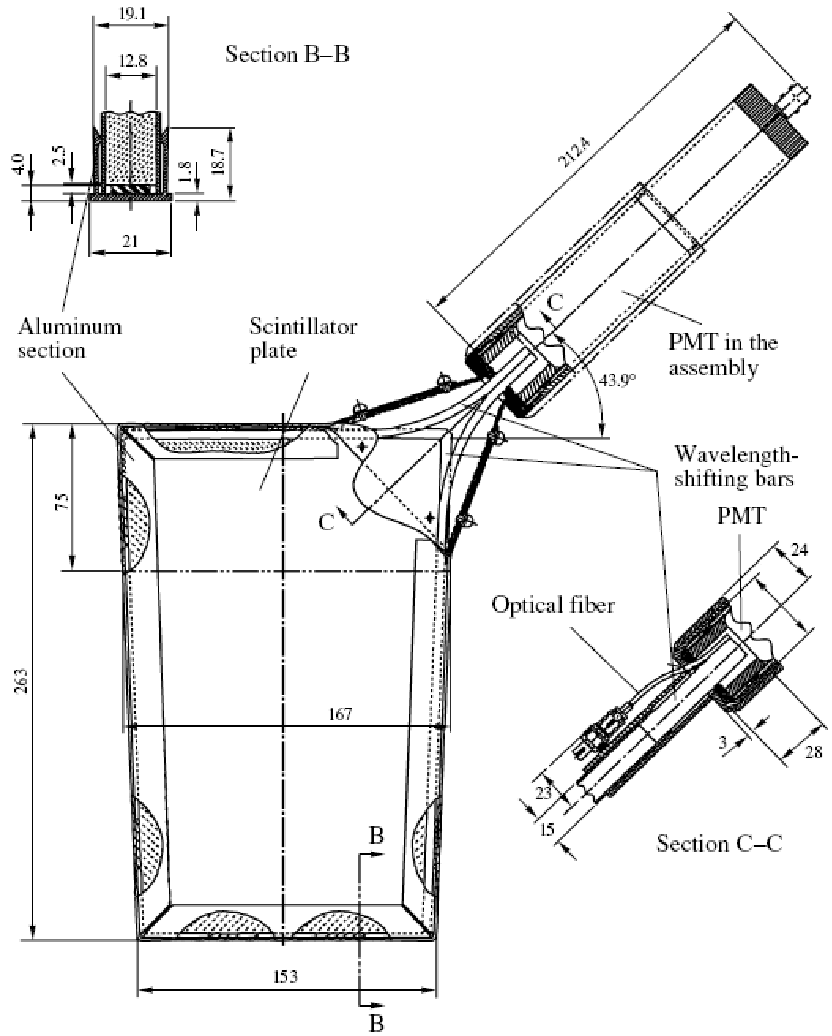

Fig. 3. Schematic diagram of the scintillation counter.

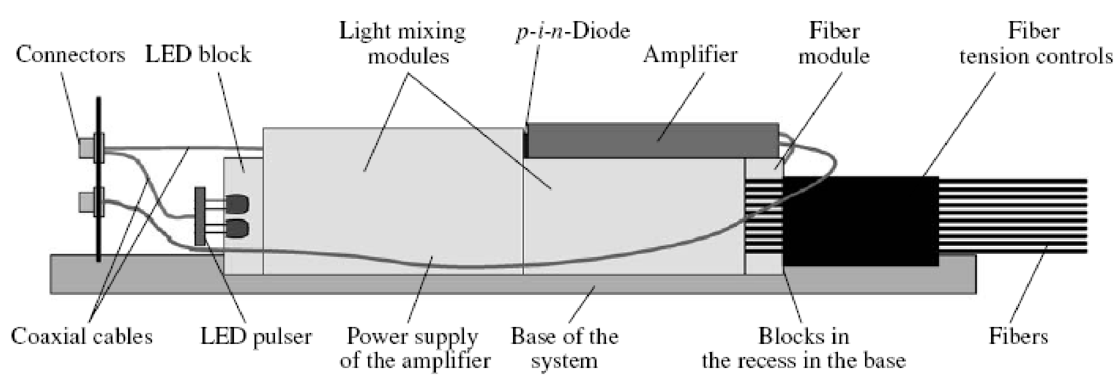

Fig. 4. Module of the LED-based calibration system.

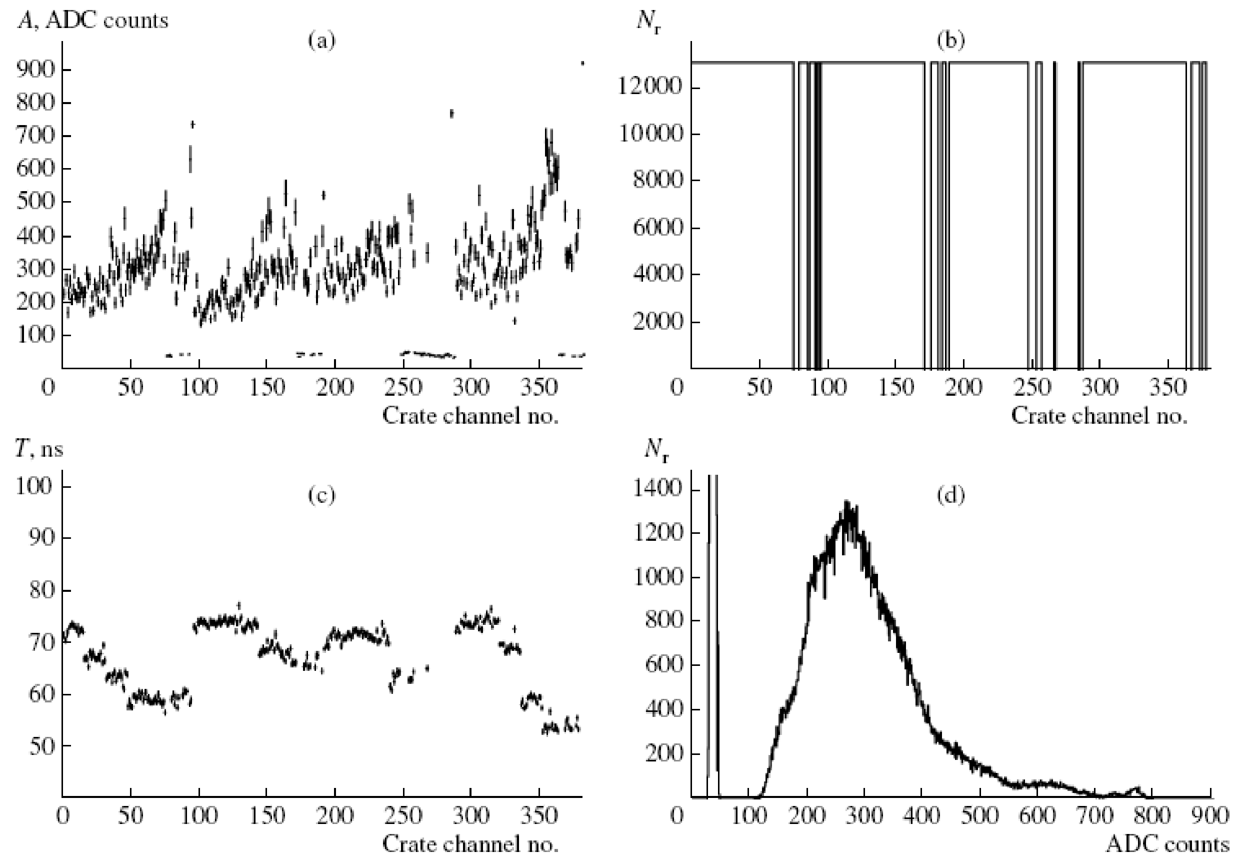

Fig. 5. Results for the SCE crate, obtained during the LED-based calibration: (a) profile of the mean amplitudes (A is the mean amplitude in the selected channel in terms of the ADC counts), (b) distribution in activated channels (N_r is the number of readouts in this channel), (c) profile of the mean times (T is the mean time value in this channel), and (d) total amplitude distribution for 384 channels (N_r is the number of readouts with a fixed amplitude value).

2001, and its results were used as reference data in all subsequent calibrations.

Calibration is done according to the following procedure. In the absence of the beam in the Tevatron collider, the high voltage at the counters is held at a level of 50% of its operating value. Before the calibration, the crate with the readout electronics for the scintillation counters of the forward muon system is switched into a local operating mode. The high voltage is raised to the operating value. Using a special program, the parameters corresponding to the values obtained in 2001 (the delay times, the masks, etc.) are loaded into the crates with the electronics. Then, the LED pulser parameters (the amplitude and the delay time) are loaded for each octant, and the calibration procedure begins.

RESULTS OF LED-BASED CALIBRATIONS OVER 4-YEAR OPERATION

The typical results of the LED calibration are presented in Fig. 5. These distributions were obtained for the South C East working crate (the southeast *C* layer, SCE), which contained four octants: SC0, SC1, SC6, and SC7. (In Fig. 2, these octants constitute the left half of the layer.)

Figure 5b presents the distribution in the triggered channels, which reflects the number of signals recorded in each channel of this crate. The channels are assigned numbers from 0 to 384. The first 96 channels correspond to zero octant SC0, the next 96 channels correspond to octant SC1, etc. From Fig. 5b, it is apparent that an LED in each channel was turned on ~13200 times in the course of calibration. Zero counts (dips in the figure) correspond to channels with nonexistent or dead counters. Each time when the signal is read out, the time between the *beam intersection* signal and the instant when the PMT signal reaches the discriminator threshold (7 mV)—i.e., the mean time of the PMT signals—is measured. The multiplexing measurement allows the signal amplitude in one event to be read out of only one counter of the high-voltage group selected. The profile of the mean times measured for all the 384 channels is presented in Fig. 5c, and the profile of the

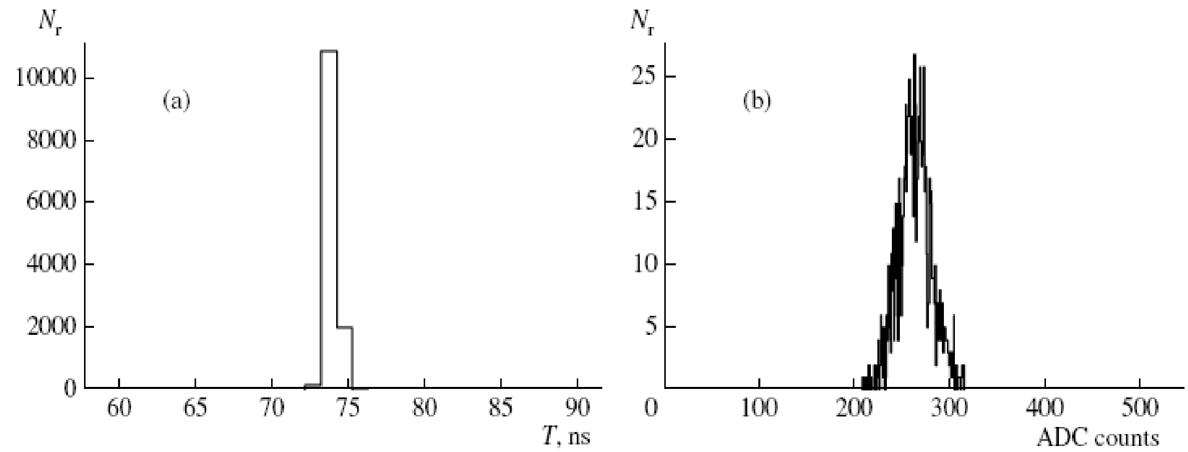

Fig. 6. Results for counter SC0-5, obtained during the LED calibration: (a) time distribution (N_r is the number of readouts with a fixed time value), (b) amplitude distribution (N_r is the number of readouts with a fixed amplitude value).

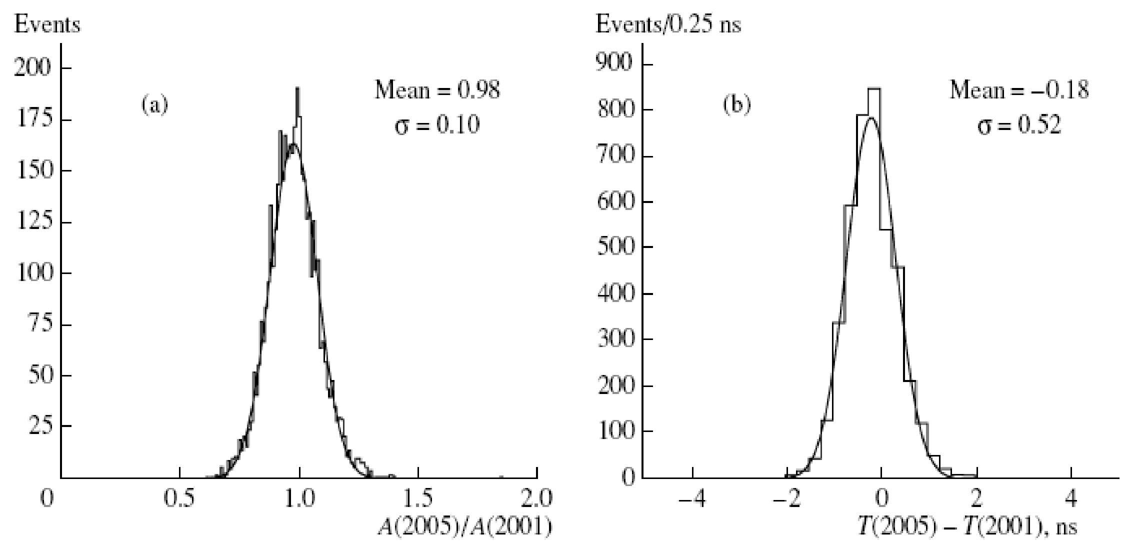

Fig. 7. Results of the calibration in 2005 (in comparison to 2001): (a) amplitude ratio $A(2005)/A(2001)$ and (b) difference of times $T(2005) - T(2001)$. One counter (SB2-73) of 4214 was dead during the calibration.

mean amplitudes is shown in Fig. 5a. In this case, the pedestal values of the SFE channels are recorded for nonexistent or dead counters (their typical values are in the range of 30–50 ADC counts). Should the SFE module be replaced, the pedestal values of all relevant channels change; therefore, they must be measured once again before the next calibration. These values are subsequently subtracted from the measured amplitudes during LED data processing. Finally, the total amplitude distribution for all the 384 channels of this crate is shown in Fig. 5d.

The data were processed according to the following procedure: the pedestal value for each channel was subtracted from the amplitude value (a similar operation was preliminarily performed for the reference data of 2001), and the result obtained thereby was divided by the reference value. This ratio was then normalized to the amplitude ratio of the *p–i–n* diode (minus the pedestal values) for the same sets of data.

The results of the LED calibration of 2005 are presented in Fig. 7. The distribution of amplitude ratios, each of which was obtained according to the above procedure, is shown for all counters in Fig. 7a. The mean

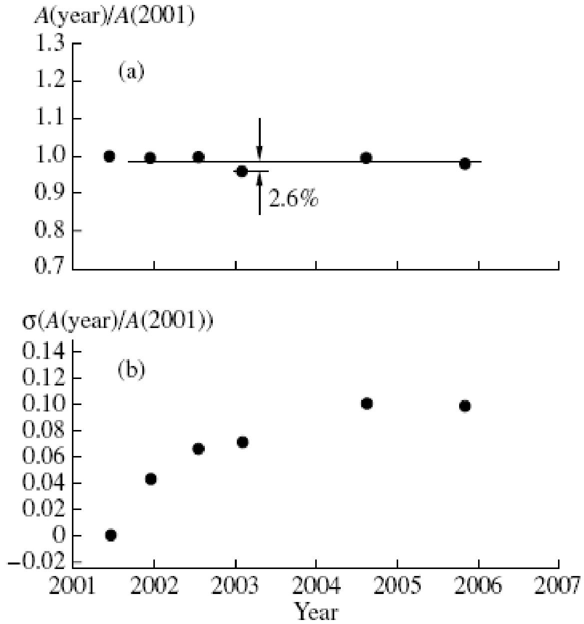

Fig. 8. Variations in the parameters of the amplitude distributions for four years: (a) variations in the mean amplitude ratios (the statistical errors of measurements are smaller than the size of a point; the maximum deviation in fitting the data by a straight line is 2.6%) and (b) changes in variance σ of the distribution of deviations. The first point in (a) and (b) is the reference point.

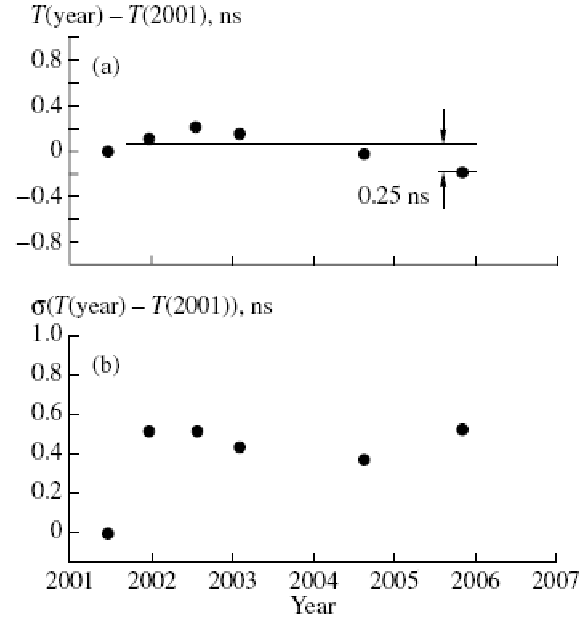

Fig. 9. Variations in the parameters of the time distributions for four years: (a) variations in the mean values of the time difference (the statistical errors of measurements are smaller than the size of a point; the maximum deviation in fitting the data with a straight line is 0.25 ns) and (b) changes in variance σ of the distribution of deviations. The first point in (a) and (b) is the reference point.

obtained in 2001 was subtracted from the corresponding value as of 2005. The mean value of the time difference was –0.18 ns with $\sigma = 0.52$ ns (Fig. 7b).

The results of the LED calibration over 4 years—the mean amplitude ratios and the mean values of the time difference—are presented in Figs. 8 and 9, respectively. The first point in each plot corresponds to the reference set of data of 2001. Figure 8 shows that the mean value of the amplitude ratio remained invariable within the limits of 4%, and variance σ of the distribution of deviations over all counters was stabilized at a level of 10% for the first 2 years of measurements. Figure 9 demonstrates a high stability of signals over time within the limits of 0.23 ns with σ of the distribution of deviations equal to 0.52 ns.

A PROCEDURE OF CALIBRATION USING MUONS

Apart from the calibration using LEDs, the stability of the performance of the scintillation trigger detector was tested by calibrating the counters using muons produced by proton–antiproton collisions during Run II of the D0 experiment.

The amplitudes of the signals induced in the counters by charged particles passing through them are measured in the course of data acquisition. The amplitude distributions for all 4704 SFE channels (the number of electronic channels exceeds the number of counters, which is 4214) are plotted on the logarithmic and linear scales in Figs. 10a and 10b, respectively. The peak in the region of 40 ADC counts corresponds to the pedestal values of all the electronic channels used in the measurements, and the peak in the region of 165 ADC counts is due to signals from minimum ionizing particles (MIPs). As was the case with the LED calibration, the signal amplitude for only 1 of 16 counters of a particular high-voltage group is read out in one event. A long time is needed for acquisition of sufficient statistics for each of the 4214 counters, which makes the channel-by-channel calibration of all the counters unfeasible. In this connection, amplitude calibration was performed for octants.

To extract muon events from the whole body of data, a procedure was developed based on the correlation between operations of counters in different layers of the muon system. Only those events were processed in which counters were triggered in each of the three layers (A, B, and C) in the southern part of the D0 detector or in the northern part in adjacent counters of octants with equal numbers. A counter is considered to be adjacent to the counter under investigation if the last figure of its sequential number differs by ±1 from that of the counter under investigation and the number of the row

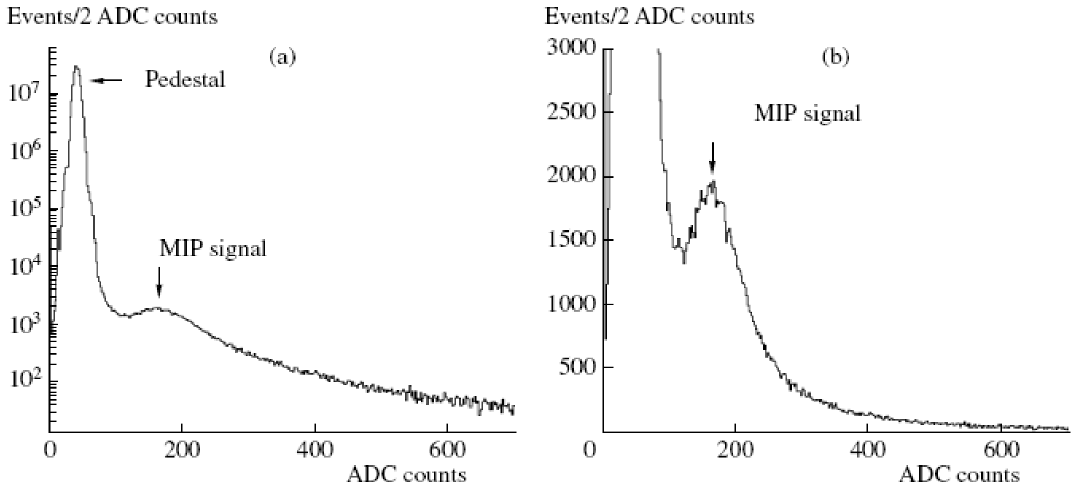

Fig. 10. Amplitude distributions for all the 4704 SFE channels (the data of 2002) (a) on the logarithmic and (b) linear scales.

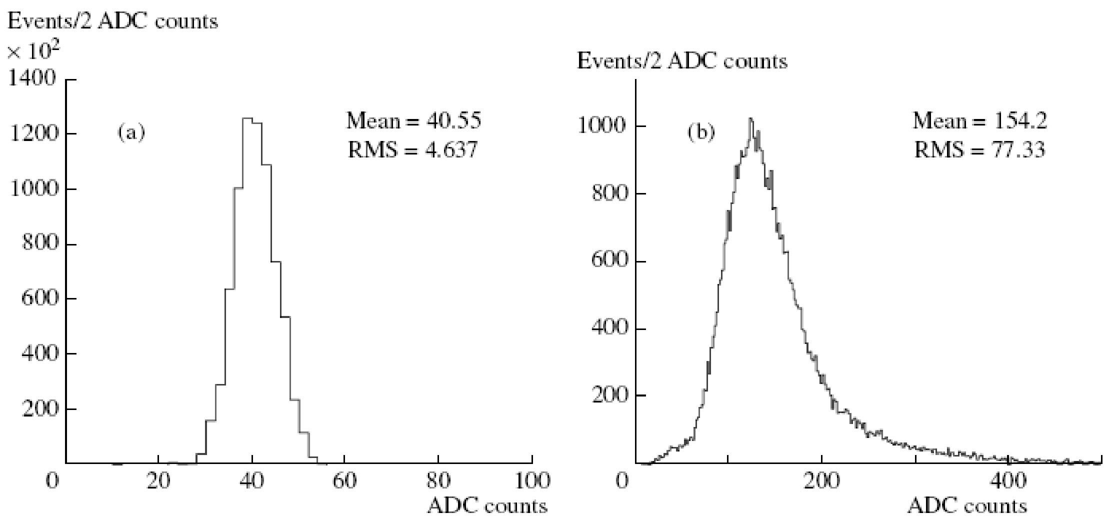

Fig. 11. (a) Distribution of pedestals and (b) amplitude distribution of muons extracted using the triggering technique, for all the 4214 counters (the data of 2002). The root-mean-square deviation is denoted by RMS.

where it is located differs by ±2. For example, if counter NC1-37 (1 is the octant number in northern (N) layer *C*, and 37 is the sequential number of the counter) is triggered, it is checked whether any counter in octant NB1 (the first octant of northern layer *B*) with one of the sequential numbers 16–18, 26–28, 36–38, 46–48, and 56–58 is also activated (see Fig. 2). Should this happen, a similar procedure is used to check whether any other counter in octant NA1 (the first octant of northern layer *A*) is triggered. If so, the whole body of data on these three operations (the number of activated counter, the amplitude, the pedestal value, and the time of operation) is used in subsequent processing.

RESULTS OF CALIBRATION USING MUONS

The above procedure was practiced for the first time in 2002. More than 6×10^5 events that had passed through the muon trigger of the D0 detector were processed. The distribution of the pedestals and the amplitude distribution of signals from muons extracted according to the above-described triggering technique are presented in Fig. 11. Though the time selection cri-

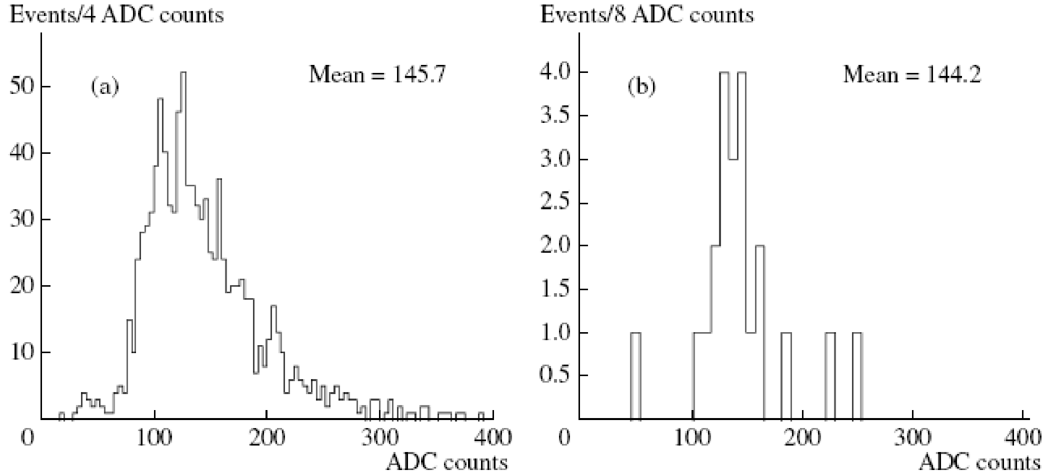

Fig. 12. Amplitude distributions (a) for octant NC0 and (b) counter SB7-54 (the data of 2002). This counter has a greater statistics than the others.

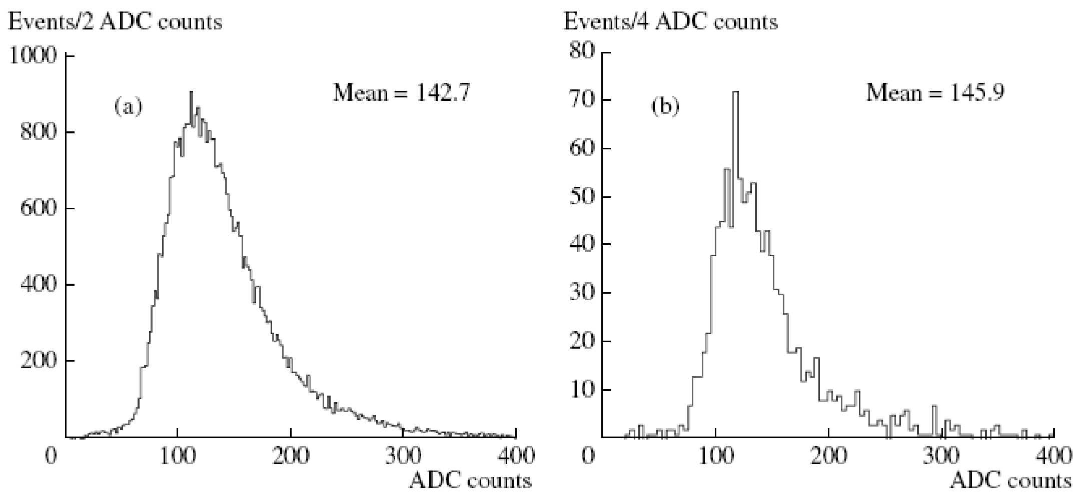

Fig. 13. Amplitude distributions (a) for octant NC0 and (b) counter SB7-54 (the data of 2006).

teria have not been used, the amplitude distribution shows that signals of ≥98% of muons extracted thereby have an amplitude corresponding to the MIP energy.

Figure 12 presents the amplitude distributions for octant NC0 and counter SB7-54 that had the greatest statistics in 2002.

To test the stability of the counters performance, a similar procedure was performed in 2006, when the software for online data processing was substantially improved, which accelerated the data acquisition process. In 2006, more than 3.45×10^7 events that passed all the triggers of the D0 detector (without selection of muon triggers) were processed. The amplitude distributions for octant NC0 and counter SB7-54, which are presented in Fig. 13, are in good agreement with the results of 2002 (Fig. 12). The total amplitude distribution for all the 4214 counters is shown in Fig. 14a.

Due to the limited statistics (let us recollect that the signal amplitude in a detected event is measured in only one of the 16 counters of a high-voltage group), the mean values of the amplitude responses were compared for octants. Results for all the 48 octants are presented in the table. The mean amplitude value obtained for each octant in 2006 was divided by the corresponding mean value of 2002.

From the table and Fig. 14b, which depicts the data of the table, it follows that the mean amplitude ratio is 0.99 and the maximum deviation from unity is 9%.

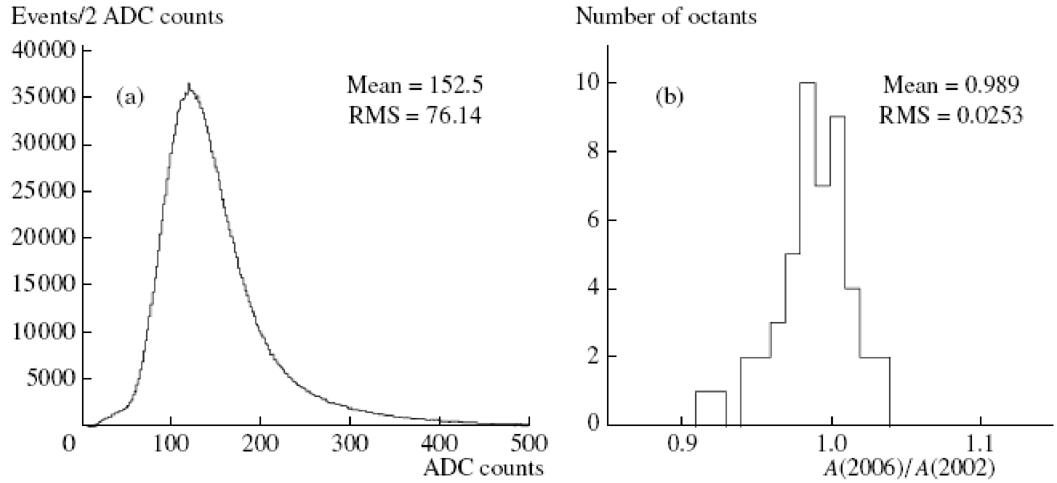

Fig. 14. (a) Amplitude distribution of muons extracted using the triggering technique, for all the 4214 counters (the data of 2006); and (b) distribution of the ratio of the mean amplitudes $A(2006)$ obtained in 2006 to amplitudes $A(2002)$ measured in 2002, for 48 octants (these data are presented in the table).

Therefore, no appreciable indications of ageing of counters were detected over 4 years of operation.

CONCLUSIONS

A procedure for LED-based calibration of the scintillation detector for the forward muon system of the D0 experiment at the Fermilab Tevatron collider (Batavia, United States) has been described. This procedure was used for the first time in 2001. The calibration results obtained in the period of 2001–2005 are presented. The mean deviation of the signal amplitudes, averaged over 4214 counters for a period of 4 years, does not exceed 4%, and variance σ of the distribution of these deviations over all counters is ~10%. In this period, the signals remained stable in time within the limits of 0.23 ns, and the variance of the distribution of these deviations was $\sigma = 0.52$ ns.

Ratio of the mean amplitudes obtained in 2006 to the mean amplitudes measured in 2002 for all 48 octants (the rms deviation is 0.02 for all values)

Octan	North *A*	North *B*	North *C*	South *A*	South *B*	South *C*
0	0.98	0.97	0.98	1.03	1.00	0.97
1	0.98	0.97	0.95	0.97	1.00	0.99
2	1.03	0.95	0.99	1.01	0.92	0.91
3	1.00	0.98	0.98	0.96	0.99	1.00
4	1.01	0.99	1.00	1.00	1.00	0.98
5	0.96	0.98	0.96	1.03	0.94	0.95
6	0.99	1.00	0.99	1.01	0.99	1.02
7	0.98	0.98	0.98	1.00	1.01	0.97

A procedure for amplitude calibration of the detector has also been proposed. This procedure is based on measuring the response of counters to muons produced in proton–antiproton collisions at the Tevatron collider. This calibration should be used to examine the complex stability of the performance of counters, since it involves testing of the performance of the PMTs and the electronics, as well as of the scintillators and the wavelength-shifting bars. Results of calibrations made in 2002 and 2006 are presented. The variations in the absolute values of the amplitude responses are within the limits of +3%…–9%. As a result, any appreciable indications of ageing of counters during 4 years of their operation in Run II have not been detected.

Calibrations using LEDs and muons, regularly performed according to the described procedures during 4 years of operation in Run II, have demonstrated the constancy of parameters of the scintillation trigger detector for the D0 forward muon system and guaranteed thereby the reliability of all physical results obtained using this detector in the D0 experiment.

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