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Luminosity monitor based on Cherenkov counters for $p\bar{p}$ colliders

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We describe here a novel approach to luminosity measurements for $p\bar{p}$ collider experiments. We propose to use low pressure gaseous Cherenkov counters at small angles relative to the beam direction to determine the rate of inelastic $p\bar{p}$ interactions. With a propotype counter, we measured at a beam test a light yield of over 100 photoelectrons and a timing resolution of better than 50 psec. The CDF collaboration will use a detector based on this technique for luminosity measurements at the upgraded Tevatron collider.

1. Introduction

The luminosity for hadron collider experiments can be determined from the rate of inelastic $p\bar{p}$ interactions. This process has a large cross section measured with an uncertainty of approximately 3% [1] and can provide a precise and fast measurement of the luminosity. Traditionally, scintillating counters are used for this purpose. Here we describe a novel approach to the registration of inelastic $p\bar{p}$ interactions using low pressure gaseous Cherenkov counters placed at small angles relative to the beam direction. This work has been done for the CDF detector at the Tevatron $p\bar{p}$ collider at Fermilab. The Tevatron is currently being upgraded to provide a peak luminosity of $2 \cdot 10^{32}$ cm^{-2}s^{-1}, corresponding to an average of about 6 inelastic $p\bar{p}$ interactions per bunch crossing in the 36×36 bunches mode.

CDF is a general purpose detector described in detail elsewhere [2]. A quadrant of the detector is shown schematically in Figure 1.

The plug calorimeter covers the region from 37° to 3° relative to the beam axis in polar angle θ, leaving free a conical hole with the beampipe in the center. The hole will be occupied by the luminosity monitoring detector, which is composed of a well segmented array of counters as shown schematically in Figure 1. Each counter consists of a gas filled truncated cone 2 m long and a few

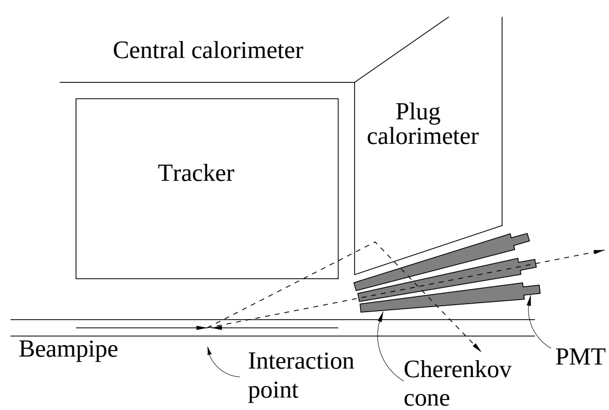

Figure 1. Schematic view of the luminosity monitor inside a quadrant of CDF.

cm in diameter made of aluminized mylar. The cones are oriented with their small end pointing to the interaction point. The Cherenkov light produced by charged particles radiating in the gas inside the cone is collected at the large end of the cone by a fast photomultiplier tube (PMT). The PMT pulse timing and amplitude are measured, digitized and read out with associated electronics.

The Cherenkov light emission angle θ_C is determined by the gas refraction index n and the particle velocity β :

$$\cos\theta_C = \frac{1}{n\beta} \tag{1}$$

The number of photoelectrons produced by a charged particle, $N_{p.e.}$, in Cherenkov counters is proportional to the length of particle's path L inside the counter and to $\sin^2\theta_C$ [4].

$$N_{p.e.} = N_0 \cdot L \cdot \sin^2\theta_C \tag{2}$$

$$N_0 = 370 \text{ cm}^{-1} \text{ eV}^{-1} \int \epsilon_{coll}(E)\epsilon_{PMT}(E)dE \tag{3}$$

The counter design specific parameter, N_0, is determined by averaging the light collection efficiency ϵ_{coll} and the PMT quantum efficiency ϵ_{PMT} over the photon energy spectrum. A PMT with quartz window improves ϵ_{coll} by collecting more efficiently the ultraviolet part of the spectrum.

Isobutane is a good choice for the Cherenkov radiator because it has a good transparency and one of the largest refractive indices at normal pressure among commonly used gases [3]. Depending on N_0, the expected signal for a 2 m long counter filled with isobutane at normal pressure ($\theta_C = 3.1^o$) can be as large as 100 photoelectrons (p.e.).

Since the angle θ_C is small, the light experiences only few reflections at grazing angles to the cone's wall, and is collected very efficiently by the PMT for particles travelling along the cone's axis. All emitted photons arrive at the end of the cone very close in time resulting in an excellent intrinsic time resolution.

The Cherenkov counter approach to measure luminosity has several advantages over the one based on scintillator counters. Primary particles from $p\bar{p}$ interactions travel along the cone's axis and produce a large signal, whereas secondary particles produced in the beam pipe and plug calorimeter cross the counter at different angles. They have short paths inside the cone and give a small amount of light. The light is reflected many times before reaching the PMT and has large losses due to the reflections. In addition, the Cherenkov counter is not sensitive to low momentum particles since it has a momentum threshold (2.2 GeV/c for pions in isobutane at normal pressure). Also, the counter is not sensistive to particles coming from beam halo interactions. These particles hit the counter from behind and, therefore, emit light in the opposite direction. In contrast, scintillating counters are sensitive to all charged particles and to a fraction of neutrons and photons.

2. Results of Monte-Carlo simulations

We studied the response of the luminosity monitor to inelastic $p\bar{p}$ interactions using the simulation package CDFSIM which simulates electromagnetic and nuclear interactions of particles in the CDF detector materials and propagates all particles through the detector accounting for the magnetic field. The $p\bar{p}$ interaction time and position along the beam direction were simulated taking into account a longitudinal interaction region r.m.s. spread of 28 cm.

Several possible variants have been studied both with Cherenkov and scintillating counters. We describe here an optimal design with 48 Cherenkov counters per side arranged in 3 layers. The 2 m long truncated cones are positioned in the 3° hole at the distance between 200 cm and 400 cm from the interaction point along the beam axis. The cones point to the interaction point and cover a region in pseudorapidity of $\Delta\eta = 0.9$ where $\eta = \ln\tan(\theta/2)$. Figure 2 shows the transverse cross section of the simulated luminosity monitor.

The light yield from the Cherenkov counters was calculated taking into account the geometrical path of the particles inside the cones, the reflectivity of the cone's wall and the threshold

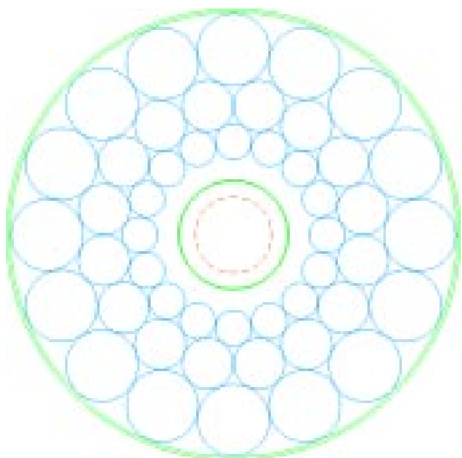

Figure 2. Transverse cross section of the simulated luminosity monitor with 48 counters per side arranged in 3 layers.

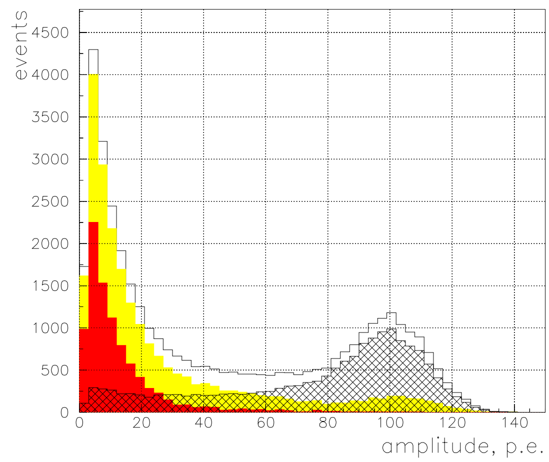

Figure 3. Simulated amplitude distribution in the Cherenkov counter for particles from inelastic $p\bar{p}$ interactions in the CDF detector. See explanations in the text.

behaviour of the Cherenkov radiation. An amplitude of 100 p.e. with a Poisson variation was assumed for a particle traversing the cone exactly along the cone's axis. Figure 3 shows the simulated amplitude distribution in the Cherenkov counters of the described above design for particles from inelastic $p\bar{p}$ interactions. The solid line corresponds to all particles, and the hatched histogram corresponds to the primary particles. The gray histogram is the contribution from all secondary particles, and the contribution from secondaries in the plug calorimeter alone is shown in the black histogram.

The peak at 100 p.e. corresponds to particles coming from the interaction point and traversing the full length of the counter. The secondary particles from the plug calorimeter and the beam pipe yield small amplitudes. Therefore, primary particles can be efficiently selected by a large amplitude requirement.

Amplitude fluctuations in Cherenkov counters are dominated by statistics of photoelectrons because the Cherenkov threshold is high enough for δ-electrons not to emit light. Otherwise, the δ-electrons would cause large Landau fluctuations in the amplitude as in the case with scintillators. The amplitude resolution in the single particle peak is equal to approximately 13% with the main contribution coming from photostatistics. Figure 4 shows the total amplitude distribution in one counter simulated for 5 inelastic $p\bar{p}$ interactions in a bunch crossing.

All particles crossing the counter contribute to the signal. At high luminosity, two or more particles may cross the counter. Two particles give double amplitude of about 200 p.e. if they both traverse the full length of the counter. The amplitude resolution is good enough to distinguish one and two particles in the Cherenkov counter.

This is a significant feature of the luminosity measurement because a detector counting particles does not saturate at high luminosity as it would if only the hit segments were taken into account. Figure 5 shows the number of particles (triangles) and number of hit segments (dots) reconstructed on one side of the luminosity monitor as function of the average number of $p\bar{p}$ interactions per beam crossing, μ, which is proportional

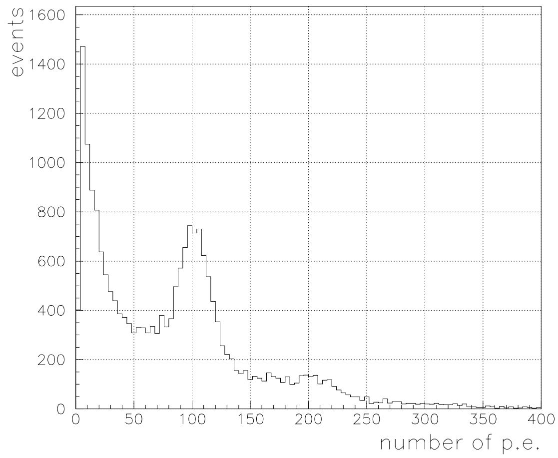

Figure 4. Amplitude distribution from the Cherenkov counter simulated for 5 inelastic $p\bar{p}$ interactions in a bunch crossings in CDF. The signal is formed by all particles crossing the counter.

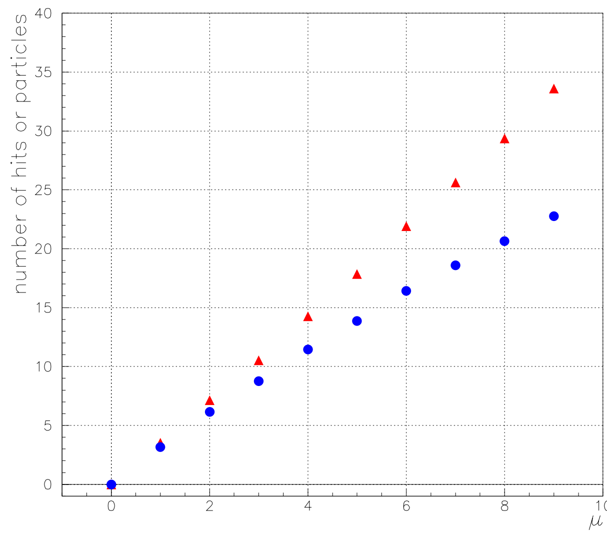

Figure 5. Number of particles (triangles) and number of hit segments (dots) as function of average number of $p\bar{p}$ interactions, μ.

to the luminosity. A 70 p.e. amplitude threshold was used to count hit segments and three thresholds, at 70 p.e., 160 p.e. and 250 p.e., were used to count particles. One can see, indeed, that counting the number of particles is more linear than counting the number of hits.

3. Luminosity monitor prototype and test beam setup

In order to test this approach we built a gas Cherenkov counter prototype and studied it with a 150 GeV pion test beam at Fermilab [6]. The main goals of the test beam studies were to measure the light yield and timing resolution for different types of gases, light collection schemes and PMTs.

Figure 6 shows the luminosity counter prototype used in the test beam. The essential parts of the prototype: the cone, the light collector and the PMT with its base were assembled inside a gas volume.

The cones were made out of two layers of 50 mi-

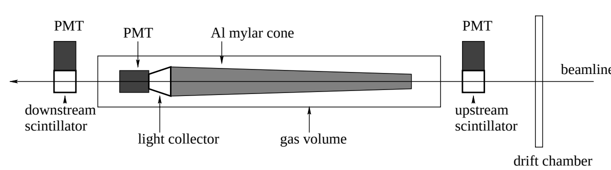

Figure 6. Schematic view of the Cherenkov counter prototype and the test beam area.

cron thick aluminized mylar wrapped in a spiral structure. The thickness of the aluminum coating was approximately 20 nm. The largest and smallest diameters of the 205 cm long cone were equal to 4.2 and 2.0 cm respectively. The aluminized side of the mylar formed the inner surface and served as a mirror.

The light collector has a conical shape to focus the Cherenkov light from the large end of the cone to the PMT photocathode active area. The largest and smallest diameters of the 4.2 cm long collector were equal to 4.2 cm and 1.8 cm respectively. The dimensions were optimized to give the maximum collection efficiency. We tested two types of collectors with different inner surfaces. The first collector was made out of the same aluminized mylar as the cone. The second collector was made of lucite with the inner surface polished to optical quality and covered first with 50 nm of Al and then with 50 nm of MgF_2. This type of surface provides good reflectance in the ultraviolet region of the spectrum [5].

We selected three different PMT types from Hamamatsu (R2076, R5800Q, R7057) [7] and one from Phillips (XP2978) [8] with dimensions (1.9-2.7 cm diameter) appropriate to our design constraints. All the PMTs have good timing resolution and quartz entrance windows. The operational voltages for the PMTs were chosen to correspond to a gain of about 10^6. We also used a larger well known PMT XP2020Q from Phillips [8] to measure the light yield from different gases and collector efficiencies.

The prototype was placed inside a gas volume consisting of an aluminum tube 10 cm in diameter and 230 cm long closed with gas tight end-plates. A simple gas system with a pump was able to maintain a stable pressure in the gas volume in the range from 0.03 to 2.0 absolute atm.

Figure 6 also shows the schematic view of the testbeam area. Two fast scintillating counters (one upstream of the Cherenkov counter and one downstream) were used for timing measurements. These counters, made of $2.5 \times 2.5 \times 2.5$ cm^3 pieces of Bicron 404 scintillator, were attached to R5946 PMTs [7]. Upstream of the prototype, a wire drift chamber measured the particle's position transverse to the beam direction with a precision of 0.3 mm. This information was used to determine the perpendicular distance from a track to the PMT axis. The beam had a negligible angular spread with respect to the beamline and transverse dimensions of approximately 3 cm. All components inside the gas volume and the scintillating counters were carefully aligned with respect to the beamline with a precision of a millimeter.

The signals from the Cherenkov and scintillating counters were carried by 30 m of coaxial cable into the readout electronics. The amplitude measurement was made with a LeCroy ADC1885F module using 10% of the signal. The other 90% of the signal was used for timing measurements made with a LeCroy TDC1875A module after a linear discriminator LRS 621L with a threshold of 25 mV.

For each PMT the absolute amplitude calibration of the electronics was determined from the single photoelectron amplitude spectrum. A blue light emitting diode (LED) Ledtronix BP280CPB1K positioned near the cone entrance was pulsed with a generator. The amplitude of the pulses was chosen such that in approximately 15% of cases the LED light produced a pulse in the PMT ensuring mostly single photoelectron production.

4. Amplitude measurements

We measured the Cherenkov counter light yield using the XP2020Q PMT. This PMT has a large photo-cathode (4.4 cm diameter) fully covering the large end of the cone so no light collector is needed. The contribution of the Cherenkov light from the PMT quartz window has to be subtracted to determine the light yield from the gas alone. This contribution can be directly measured by evacuating the gas. Under vacuum only the window produces the Cherenkov light as particles traverse the counter.

The upper plot in Figure 7 shows the signal amplitude as a function of distance to the PMT center for isobutane at 1.47 absolute atm (upper curve) and for vacuum, 0.03 absolute atm (lower curve). The lower plot in the same figure shows the difference between the two curves, which corresponds to the gas contribution alone. The flat

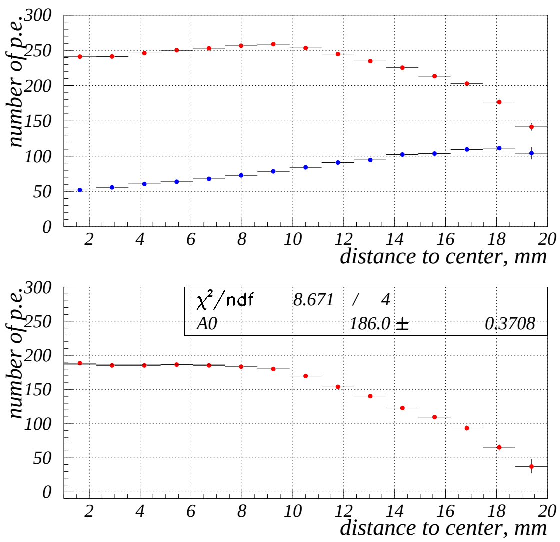

Figure 7. XP2020Q PMT. Upper plot: amplitude as function of distance to the PMT center for isobutane at 1.47 absolute atm (upper curve) and for vacuum, 0.03 absolute atm (lower curve). Lower plot: difference between the two curves in the upper plot. This is the amplitude contribution from isobutane alone. The flat part of the distribution is fit with a constant.

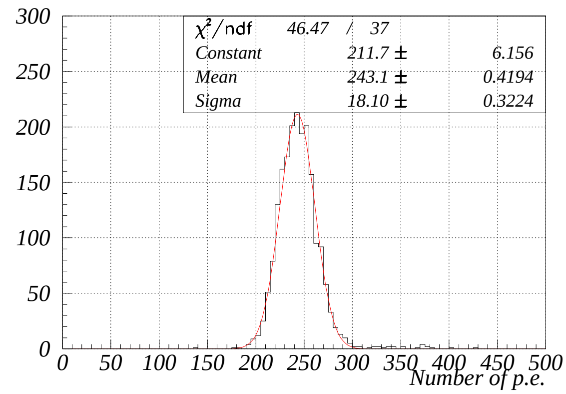

Figure 8. PMT XP2020Q. Amplitude distribution for the region around the PMT center for isobutane at 1.47 absolute atm. The distribution is fit with a gaussian.

part of this distribution, at small distances to the PMT center ($\leq$ 10 mm), corresponds to the situation when a particle traverses the full length of the cone. The observed signal in this region is 129$\pm$5 p.e. per 1 atm of isobutane corresponding to N_0 = 215 cm^{-1}. At larger distances ($\geq$ 10 mm) particles start to miss the entrance and enter the cone from the side surface, resulting in decreased signal.

A gaussian fit to the amplitude distribution for the region near the PMT center (distance to the center $\leq$ 5 mm) is shown in Figure 8. The mean of the distribution is 243 p.e. with both the gas and the PMT window contributing to the signal. The width of the distribution, 18.1 p.e., is slightly larger than $\sqrt{N_{p.e.}}$ = 15.6 p.e. expected from photostatistics alone. The variable window thickness and imperfect alignment of the cone account for this difference.

We studied the relative light yields for various gases, the results are given in Table 1. We estimate an uncertainty of about 3% for all these measurements. Considering the different refractive indices, the results agree reasonably well with expectations. This also suggests that the light collection is not limited by the transparency of the gases.

We used light collectors to measure the light yield with the smaller diameter PMTs. The yield in this case is smaller than for the XP2020Q PMT because of reflection losses in the collector. We determined the collector efficiency of 81% for the aluminized mylar collector and of 86% for the lucite collector covered with MgF_2.

A light yield of 111±5 p.e. per 1 atm of isobutane was measured with the R5800Q PMT (2.5 cm diameter) and the aluminized mylar collector. The other PMTs had similar light yields, all higher than 100 p.e.

Normally, PMTs with good timing resolution have a window with variable thickness to minimize the spread of the transition time between the photocathode and the first dynode. We determined the PMT window profiles by measuring the window light yield in vacuum as a function of distance between a track and the PMT center. The results are presented in Figure 9.

The window thickness is about 0.8 mm in the PMT center for the R2076 and R7057 PMTs and about 2 mm for the other PMTs. These results show that the Cherenkov light yield in synthetic quartz (window material) is about 25 p.e. per mm.

It is desirable to decrease the PMT window thickness for a final design so the contribution from the light in the window is small compared to the gas contribution. A modified version of the R5800Q PMT with a concave-convex window shape and window thickness of 1 mm was chosen for the CDF luminosity monitor.

5. Timing measurements

Timing resolution studies were carried out by measuring the time difference between the upstream scintillating and Cherenkov counters (ΔT_{uC}), and between the upstream and downstream scintillating counters (ΔT_{ud}). Their linear combination gives the time difference between the downstream scintillating and Cherenkov counters ΔT_{dC}. Two estimates of the timing resolution for the Cherenkov counter, σ_C^u and σ_C^d, can be deter-

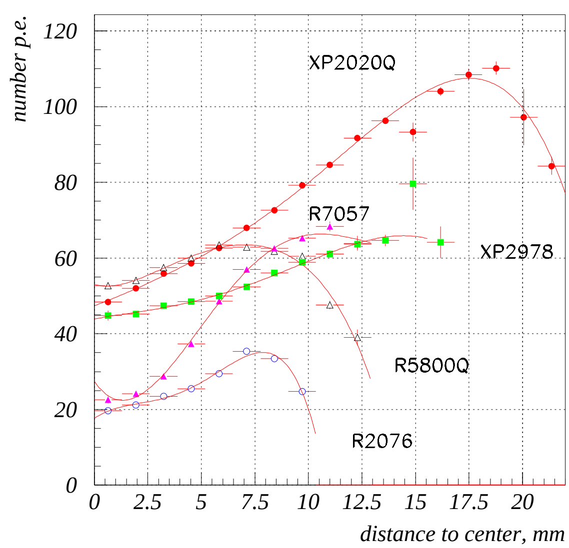

Figure 9. Light yield in the PMT window as function of distance between a track and the PMT center for various PMTs.

Table 1
Relative light yield for different gases with respect to isobutane. The uncertainty in all measurements is ±3%.

gas	iso-C_4H_{10}	C_2F_6	C_3F_8	C_4F_8	SF_6	N_2
measured yield	100%	61%	79%	86%	58%	23%
expected yield	100%	55%	74%	87%	64%	21%

mined by assuming of equal timing resolution for each of the scintillating counters:

$$\sigma_C^u = \sqrt{\sigma^2_{\Delta T_{uC}} - (\sigma^2_{\Delta T_{ud}}/2)} \quad \text{and} \qquad (4)$$

$$\sigma_C^d = \sqrt{\sigma^2_{\Delta T_{dC}} - (\sigma^2_{\Delta T_{ud}}/2)} \qquad (5)$$

A precise measurement of the timing resolution in the scintillators is important to extract the timing resolution of the Cherenkov counter. The resolution $\sigma_{\Delta T_{ud}}/\sqrt{2}$ was measured to be 50 ± 5 psec. In all timing measurements reported here, $\Delta T_{uC}, \Delta T_{dC}$ and ΔT_{ud} were corrected for the scintillator amplitude dependence.

The results of timing measurements for the Cherenkov counter with the R2076 PMT are shown in Figure 10. The upper plot shows the dependence of ΔT_{uC} on the Cherenkov counter amplitude. The middle plot shows the dependence of the timing resolution σ_C^u (dots) and σ_C^d (triangles) on the same amplitude. The similarity between σ_C^u and σ_C^d shows that both scintillating counters have indeed a very similar timing performance. Assuming a $1/\sqrt{N_{p.e.}}$ contribution from the PMT and a constant term in resolution, we fit the points to a $\sqrt{P_1^2/N_{p.e.} + P_2^2}$ function. The two lower plots show $\sigma_{\Delta T_{uC}}$ as function of distance to the PMT center and the ΔT_{uC} distribution for amplitudes in the Cherenkov counter between 75 and 125 p.e. In the last two plots ΔT_{uC} was corrected for the Cherenkov amplitude dependence.

For an amplitude of 100 p.e. the time resolution of the Cherenkov counter was measured to be 48 psec, 85 psec and 100 psec for the R2076, R5800Q and R7057 PMTs respectively. The constant term in resolution for all three PMTs was measured to be less than 25 psec which is consistent with the expected timing resolution of the

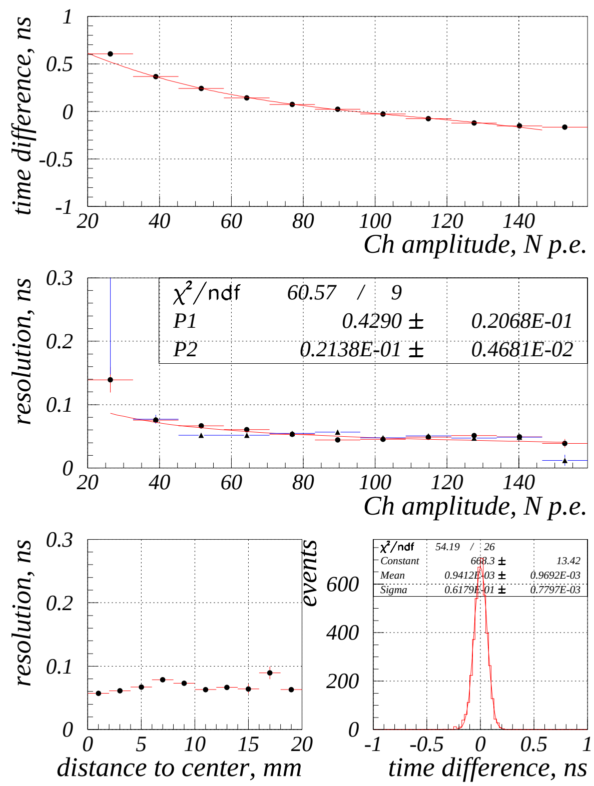

Figure 10. PMT R2076. Upper plot: ΔT_{uC} as function of amplitude in the Cherenkov counter. Middle plot: σ_C^u (dots) and σ_C^d (triangles) as function of amplitude in the Cherenkov counter. Lower left plot: $\sigma_{\Delta T_{uC}}$ as function of distance to the PMT center. Lower right plot: distribution of ΔT_{uC} for Cherenkov amplitude between 75 and 125 p.e. In the two last plots ΔT_{uC} was corrected for the Cherenkov amplitude dependence.

electronics alone. In all cases the time resolution was limited by the intrinsic resolution of the PMT itself.

It is worth mentioning here that the excellent timing resolution of the Cherenkov counters can provide another independent estimate of the luminosity. Particles from different $p\bar{p}$ interactions which occured in the same bunch crossing are separated in position and time and arrive to the counters with different delays. The measured times of arrival of all particles from a given interaction will cluster together. Different time clusters will correspond to different $p\bar{p}$ interactions. The average number of the interactions, which is proportional to the luminosity, can be, therefore, obtained from the number of the time clusters.

6. Conclusion

We have simulated the response and tested a prototype detector for luminosity measurements in $p\bar{p}$ colliders based on gaseous Cherenkov counters. The testbeam studies showed that the proposed detector has excellent amplitude and timing resolution. Light yields larger than 100 p.e. at 1 atm of isobutane have been obtained with several PMTs and light collection schemes that could be used in a final design. We measured a timing resolution better than 50 psec for the R2076 PMT and better than 100 psec for the R5800Q PMT. In both cases the resolution was limited by the intrinsic resolution of the PMT.

The ability to count primary particles while rejecting soft, secondary and beam halo particles and the precise timing information make the detector based on Cherenkov counters into an excellent instrument for the luminosity measurement in hadron colliders.

The proposed approach has been adopted by the CDF collaboration as the luminosity monitor for Run II at the Tevatron.

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