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The CDF Cherenkov Luminosity Monitor

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Abstract

We have built a novel device for precision measurements of luminosity in the CDF experiment at the high $p\bar{p}$ collision rates expected during Run II. The detector consists of long, conical, gaseous Cherenkov counters that point to the collision region and monitor the average number of inelastic $p\bar{p}$ interactions by measuring the number of particles, and their arrival time, in each bunch crossing. For these primary particles, using isobutane at atmospheric pressure as a radiator, a large amount of Cherenkov light (~ 100 photoelectrons) will be collected, with good amplitude and time resolutions, onto small and efficient PMTs. Suitable amplitude thresholds will be applied to discriminate from non-primary particles and other backgrounds which yield little light in the counters. This detector is expected to reliably perform bunch-by-bunch luminosity measurements at peak instantaneous luminosities of 2×10^{32} cm^{-2}s^{-1} with six interactions per bunch crossing, on average, and respond to a 132 ns bunch spacing.

1 Introduction

At hadron collider experiments the beam luminosity, traditionally, has been measured using dedicated scintillating counters which can measure the fraction of bunch crossings with no interactions [1,2]. These counters, typically placed at relatively large pseudo-rapidities, can have large acceptance for inelastic $p\bar{p}$ interactions, which have a well known cross-section [3], and can be used to estimate, from Poisson statistics, the average number of interactions per beam crossing, μ, and therefore the luminosity, $\mathcal{L}$, using: $\mathcal{L} = \frac{f \cdot \mu}{\sigma_{tot}}$. Where f is the frequency of bunch crossings and σ_{tot} is the total $p\bar{p}$ interaction cross-section.

However, at very high luminosities, where the average number of interactions is rather large (for the CDF Run II we expect $\mu \sim 6$), the fraction of crossings with no interactions is extremely small and very difficult to measure with a small relative uncertainty. Therefore the use of this technique to measure luminosity with precision no longer works well and it is desirable to measure the average number of interactions directly.

2 Design, Light Collection and Measurements

In order to monitor with precision the average number of $p\bar{p}$ interactions at CDF during Run II we have built a detector that can be used in a dedicated fashion, which is robust, fast, and that is sensitive mostly to particles from inelastic $p\bar{p}$ interactions and insensitive to backgrounds. The detector consists of two modules which are located in the "3-degree holes" inside the CDF end-plug calorimeters in the forward and backward region and which cover the $3.7 < |\eta| < 4.7$ pseudo-rapidity range (Fig. 1).

Each CLC detector module (for "Cherenkov Luminosity Counters") consists of 48 thin, long, conical, gas-filled, Cherenkov counters. These counters are arranged around the beam-pipe in three concentric layers, with 16 counters each, and pointing to the center of the interaction region (Fig. 2). They are built by rolling a 0.1 mm thick sheet of reflective aluminized mylar (with a 60 nm layer of Al coating) into a conical shape. For mechanical stability, the sheet is cut and rolled in such a way such that at any point the effective cone thickness is 0.2 mm. The cones in the outer two layers (further away from the beam pipe) are about 180 cm long. The inner layer counters are shorter, about 110 cm long, due to geometrical constraints. The counters' cross-sections range between two and six centimeters in diameter. At the large aperture of the mylar cones, furthest from the interaction region, we've attached conical mirrors (light collectors) made of thin aluminum (0.5 mm) and with their inner surface coated first with a 50 nm coat of aluminum and then with a 50 nm coat of MgF_2. At the small end of the light collectors we've placed fast, 2.5 cm diameter, photomultiplier tubes (Hamamatsu R5800Q). These tubes have a concave-convex, 1 mm thick, quartz window and can operate with a gain up to 2×10^6. The counters are mounted on a long ($\sim 230\ cm$), thin (0.9 mm), 10 cm diameter, aluminum tube that surrounds the beam pipe. The completed structure is enclosed in a thin, aluminum, pressure vessel, filled with isobutane. The nominal operation point is at atmospheric pressure, however, if more light is desired, the vessel is designed to operate up to one atmosphere above atmospheric pressure. High voltage and signal cables and quartz fibers (used with an LED based calibration system which flashes light into the cone's small apertures) penetrate the vessel through leak tight connectors (Fig. 2). Surrounding the vessel, in the region where the PMTs are located, we placed a cylindrical, soft-iron, magnetic field absorber, such that the fringe CDF solenoid field (which is about 200 Gauss and mainly along the PMTs axis) is reduced to a point where thin (0.5 mm), individual, mu-metal shields allow each PMT to operate without any gain loss.

We use isobutane as a radiator for it has one of the largest indexes of refraction at atmospheric pressure for commonly available gases (1.00143) and good transparency for photons in the ultra-violet region where most of the Cherenkov light is emitted. The Cherenkov light cone half-angle, θ_c, is 3.1^o and the momentum threshold for light emission is 9.3 MeV/c for electrons and 2.6 GeV/c for pions.

The expected number of photoelectrons, $N_{p.e.}$, for a single counter is given by $N_{p.e.} = N_o \cdot L < sin^2\theta_c >$ with L being the distance traversed by the particle in the medium, and $N_o = 370\ cm^{-1}eV^{-1} \int \epsilon_{col}(E)\epsilon_{det}(E)dE$, where ϵ_{det} and ϵ_{col} are the light detection and collection efficiencies respectively. Our design gives $< \epsilon_{col} >\sim 0.5$; determined by two reflections on average, at grazing angles, on the mylar cone and one on the light collector. Using a PMT with a quartz entrance window (with a frequency cutoff of ~ 160 nm) increases significantly the light detection efficiency such that $\int \epsilon_{det}(E)dE \sim 1.1$ eV and therefore $N_o \sim 200\ cm^{-1}$ such that $N_{p.e.} \sim 0.6/cm$. We've verified these efficiencies and yield with a prototype counter at a test-beam at Fermilab [4].

Prompt particles coming from the $p\bar{p}$ interactions (primaries) will traverse the full length of the counter and generate a large amplitude PMT signal (~ 100 photoelectrons). Particles originating from beam-halo interactions or from secondary interactions of prompt particles in the detector material and beam-pipe (secondaries) are softer, will traverse the counters at larger angles, with shorter path lengths, and their light will suffer a larger number of reflections. Their signals are therefore significantly smaller than that of primaries and can be discriminated by using suitable amplitude thresholds in the electronics and in the data analysis stage. This is not feasible with scintillating counters. Also, for a fixed segmentation and at high occupancies, when two primary particles traverse a single counter the resulting signal is twice that of a single particle. Given that there are no Landau fluctuations (as in scintillators), the counters' amplitude distribution will show distinct peaks for the different particle multiplicities hitting the counters. These distributions allows us to count the actual number of particles and not only the number of "hits" therefore preventing the counting rate from saturating at high luminosities and allowing a more precise measurement of the average number of interactions [4]. From simulations we expect that for each $p\bar{p}$ interaction, on average, about 10 particles with momentum above the Cherenkov threshold willcross the counters in one of the CLC modules. About 50% of these are secondaries (mostly electrons).

Additionally, given the excellent time resolution for these Cherenkov counters (we measured < 100 ps resolutions at the test-beam [4]), it is possible, in order to estimate the number of $p\bar{p}$ interactions in a given beam crossing, to study the time distributions for all counters and count the number of time clusters. This provides another method of measuring luminosity, in addition to that of counting particles, which will help reduce the systematic uncertainties in the measurements.

3 Electronics and Readout

To supply the PMTs with high voltage we use CAEN A932A distributor modules within an SY527 crate. The PMT signals travel along 70 m long cables to a 9U VME crate situated outside the collision hall where the front-end electronic boards are located. A transition board splits these signals for independent amplitude and timing measurements. The amplitude signals are gated by a ~ 40 ns gate in order to integrate only the charge from the fast PMT signals. The timing signals go through an on-board discriminator and provide the "start" signals to the TDC. For amplitude digitization and readout we use the ADC VME boards [5] used by the CDF calorimeters and for timing digitization and readout we use the 1 ns/count TDC VME boards used by the CDF central tracker and muon systems [5]. In order to effectively reduce the timing bin size down to 100 ps we stretch, before inputting to the TDC, the difference between the "start" and "stop" (given by the CDF 132 ns clock) signals by means of a "time stretcher" NIM module [6].

Even though in principle the CLC amplitude and time measurments can be calibrated using data from collisions we've installed an LED driven calibration system that accomplishes this task in a controlled fashion. A bundle of quartz fibers penetrates the gas vessel through a leak tight connector and the fibers run along to the front of the detector and deliver light to the entrance of each mylar cone.

The CLC detector is read out at every trigger together with the rest of the CDF sub-systems. Additionally, a special ~ 1 Hz, fully unbiased, beam-crossing trigger will be implemented in order to create a dataset that samples the luminosity continuously through the run. This dataset will be analyzed in detail offline to produce the final luminosity measurements for the various data sets.

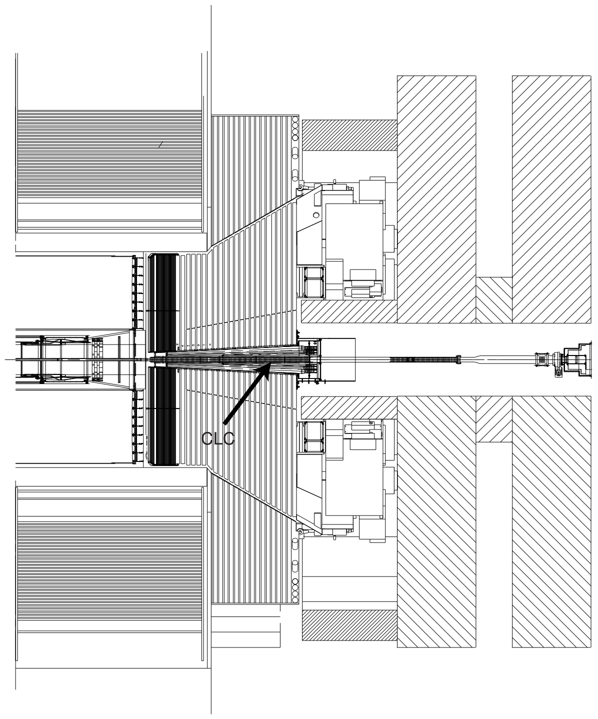

Fig. 1. The Cherenkov Luminosity Counters in CDF.

In order to obtain an luminosity measurement online we have implemented particle counting algorithms on the front-end ADC boards directly. Several suitable thresholds on the digitized signal amplitudes are implemented within field-programmable gate arrays which output the number of particles seen in each interaction. The results from these counters are sent (every 132 ns) to dual port memory boards (LeCroy 1190) in a companion 6U VME crate. These boards are read out in real time by the crate CPU, where bunch-by-bunch luminosity estimates are performed. These results are then sent to the Tevatron control room for immediate feedback ($\sim$ 1 Hz) on the collider performance. Additionally, we send these measurements to another memory module back in the 9U VME crate such that they get incorporated, albeit asynchronously, as part of the CDF event data. These numbers are then used by the CDF online data acquisition to monitor the online luminosity and the performance of the CDF trigger detector subsystems by monitoring all different trigger rates relative to this luminosity.

As of the time of this writing, June 2000, the CLC detector is completed, fully installed and all the electronic paths are operational.

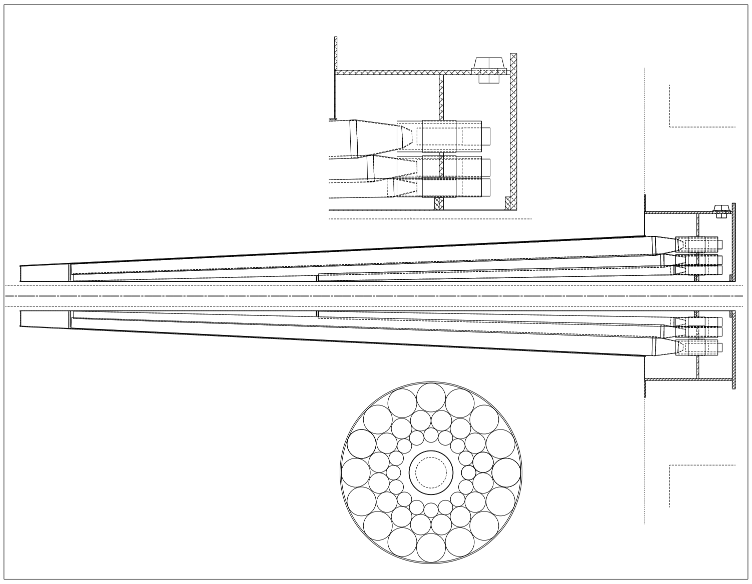

Fig. 2. The CDF Cherenkov Luminosity Counters' Desing.

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