Developing a direction-sensitive Cerenkov detector for beam monitoring applications

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Introduction

The detector protection system used at the Large Hadron Collider (LHC) to detect upstream beam-gas events is limited in its efficiency due to the very large flux of particles produced in the beam-beam collisions at the center of the detectors.

My project was an investigation into the feasibility of developing a direction-sensitive device that can detect particles coming into the main LHC detectors (e.g. the Compact Muon Solenoid) from beam-gas interactions while being insensitive to particles coming out of the main detectors from beam-beam collisions.

The device design tested exploits the directionality of Cerenkov radiation, a form of radiation produced in a forward facing cone by charged particles travelling through a transparent medium faster than the speed of light in that medium.

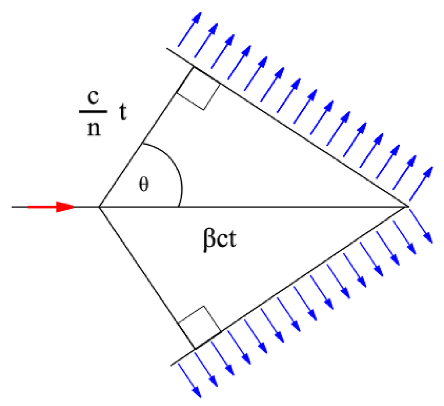
Theory

Cerenkov photons are produced in a cone whose opening angle is governed by the following equation:

$$\cos\theta = 1/n\beta$$

where *n* is the index of refraction of the radiating material and β is the ratio of the particle's velocity to the speed of light. Note that this gives rise to the threshold condition that Cerenkov radiation is only produced when $\beta > 1/n$.

The figure at right is a representation of the cone of Cerenkov photons (blue) produced by a charged particle (red):



The equation for the number of Cerenkov photons produced per unit path length is the following:

$$dN_\gamma/dx = 2\pi\alpha z^2 \int_{\beta n(\lambda)>1} \sin^2\theta \, d\lambda/\lambda^2$$

where α is the fine structure constant, *z* is the charge of the particle, and λ is the wavelength of the Cerenkov photon.

Based on this equation, approximately 5,300 Cerenkov photons between wavelengths of 300 and 800 nm would be produced by a 120 GeV proton travelling through 10 cm of plexiglass (*n ~ 1.5).*

Apparatus/Data Collection

The Cerenkov detector tested consisted of a cylinder of UVT plexiglass (4 cm radius, 10 cm long) wrapped in aluminized mylar, blackened at one end and attached to a XP2020 photomultiplier tube (PMT).

A microchannel plate (MCP) PMT was upstream from the Cerenkov detector. This PMT permitted identification of particle showers (see Analysis section for details).

Direction sensitivity determined by collecting PMT pulse height data with detector placed at angles of 0 degrees (PMT facing toward beam) and 180 degrees (PMT facing away from beam) with respect to the incident particle beam.

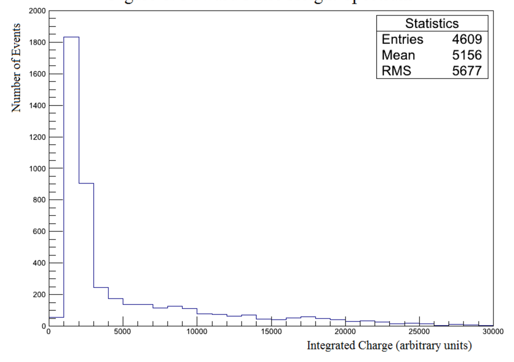
Testing carried out with a 120 GeV proton beam at the Fermilab Test Beam Facility. 5,000 events of data were taken with the detector in the forward and backward orientations.

Data compared to the result expected based on a Monte Carlo simulation performed using Geant4.

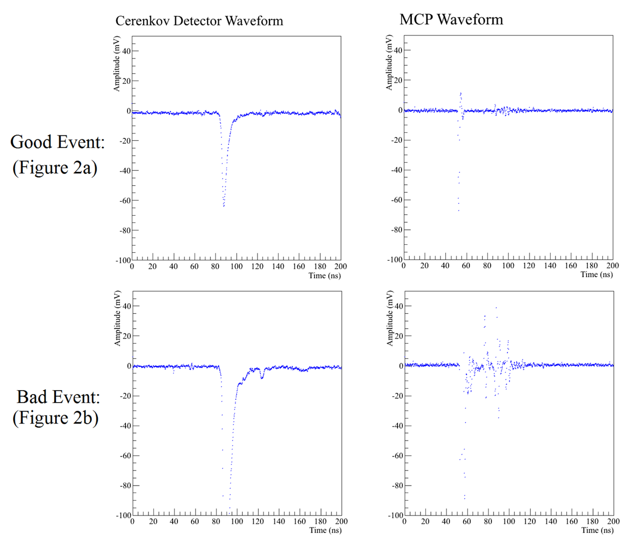
Analysis/Results

Example of data collected: Cerenkov detector PMT pulse height spectrum when placed in forward orientation (Figure 1)
- Long tail unexpected –> investigate possible causes

Figure 1: Foward Pulse Height Spectrum



Analysis of individual MCP PMT waveforms revealed that many of the events consisted of particle showers.
- Regular event (Figure 2a), particle shower event (Figure 2b)
- Possible cause of particle shower: interaction with material upstream of detector
- After implementing an algorithm to reject events having too many peaks above a set threshold, pulse height spectra recalculated yet long tail still present



2D histograms of pulse height spectra (Figures 3 and 4)
- Notice that a long horizontal tail is present in the forward direction but absent in the backward direction

Figure 3: 2D Forward Pulse Height Spectrum

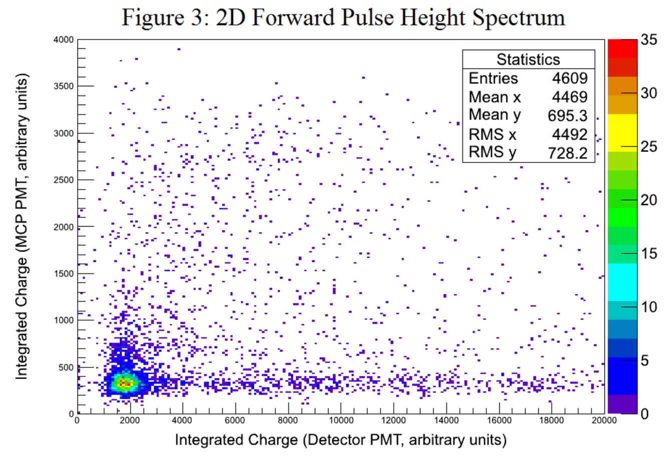
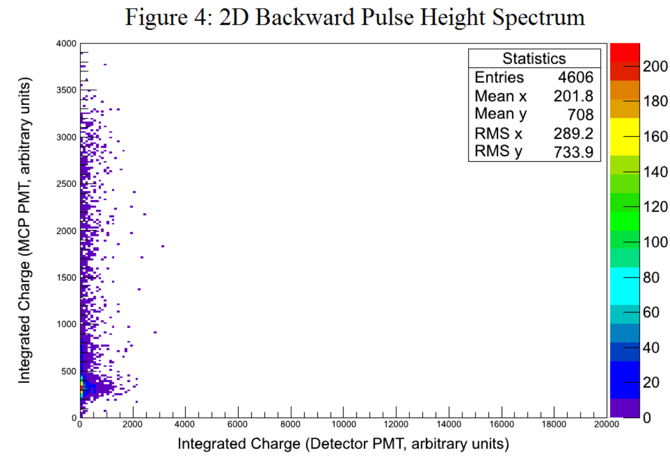
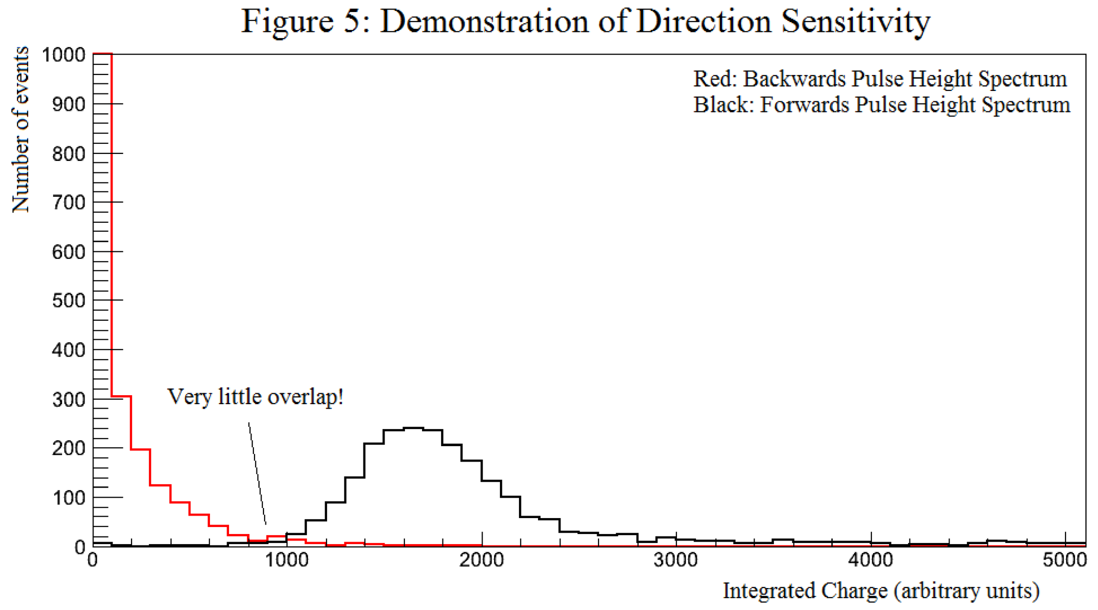


Figure 4: 2D Backward Pulse Height Spectrum



Metric of direction sensitivity: level of overlap from forward and backward pulse height spectra
- Figure 5: overlay of 2D histograms projections for MCP pulse heights between 200 and 450
- Very little overlap therefore the detector is capable of discerning particle directionality
- Detector in the backward orientation has a 98.8 ± 0.2% rejection efficiency (i.e. the direction of only 1.2% of the particles could be wrongfully interpreted)

Figure 5: Demonstration of Direction Sensitivity



Geant4 Simulation

Geant4 is a Monte Carlo based simulation program used for modeling the interaction of particles with matter.

Simulation adapted from the Geant4 tutorial program exampleN06, an optical photon process simulator.

Figure 6: Simulation results for 5,000 120 GeV protons incident on forward-facing 4 cm radius, 10 cm long G4_PLEXIGLASS bar
- Number of photons produced in bar similar to that expected from theory (see calculation in Theory section)
- Note that tail goes away when electron physics processes are turned off!

Figure 7: Simulation results under same conditions except detector rotated 180 degrees
- Photon production in bar (not pictured) stays the same but number of photons reaching PMT is very small, as expected

Figure 6: Overlay of Forward Simulation Results

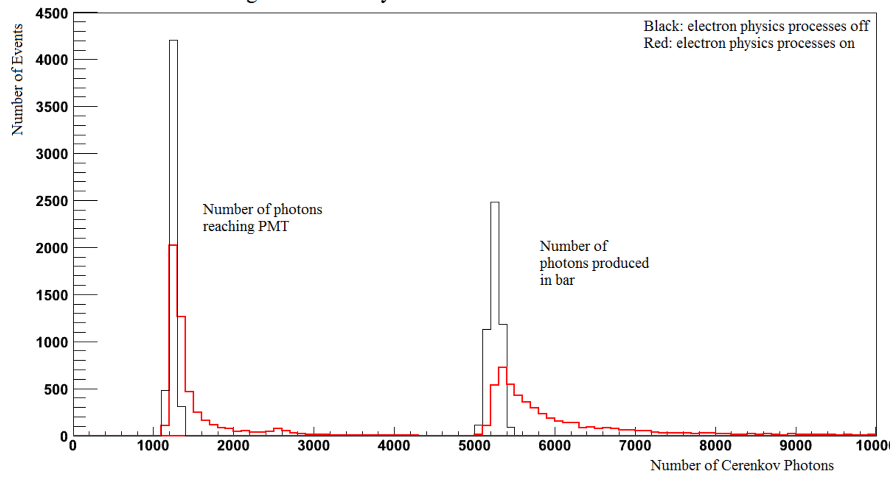
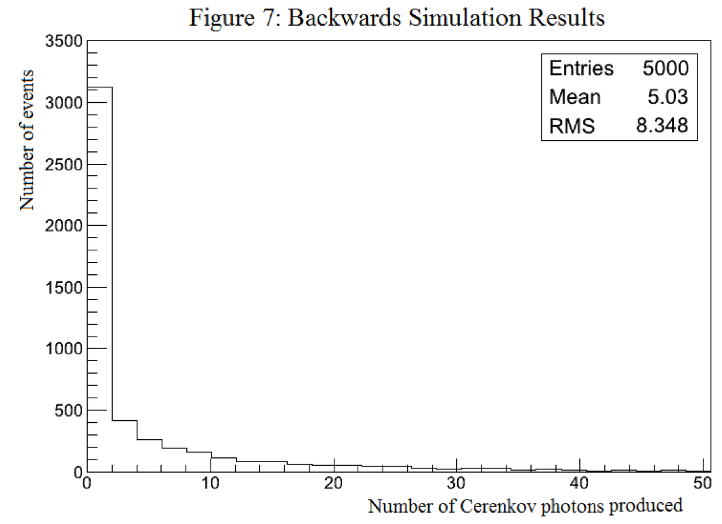


Figure 7: Backwards Simulation Results



Conclusions

Long tail in pulse height spectra potentially due to electrons liberated by the proton beam.
- Supported by the absence of a long tail in the simulation results when electron physics processes are turned off (see Figure 6)
- Supported by the absence of a long tail in the backwards pulse height spectrum (see Figure 4) since few electrons are produced in a direction opposite to the beam direction

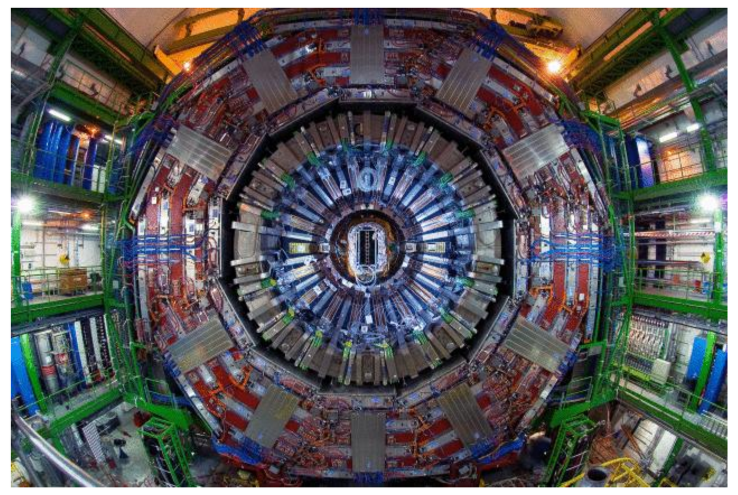
Based on the pulse height spectrum overlay (Figure 5), conclude that the detector in the backward orientation has a 98.8 ± 0.2% rejection efficiency. This value indicates that the detector design is sufficiently direction-sensitive for possible incorporation into the Large Hadron Collider beam monitoring system.

Next Steps

Perform more tests to determine if long tail really is due to electrons.

Improve Geant4 Simulation:
- Account for surface reflections (add aluminized mylar wrapping, blackened end)
- Incorporate quantum efficiency of the PMT
- Run simulations with beam not aligned along cylinder axis
- Run simulations with different particles of different energies

Take data at the LHC!
- Place detectors in LHC beam-line during 2012 technical stop
- Modify simulation and compare to new data collected



Acknowledgements

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