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Scintillating Fiber Tracking at High Luminosities Using Visible Light Photon Counter Readout

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ABSTRACT

This paper reviews the research work on the Visible Light Photon Counters (VLPC) that have been developed for the scintillating fiber tracking at high luminosity colliders and high rate fixed target experiments. The devices originated from the joint work between UCLA and Rockwell International Science Center[1][2]. The VLPCs are capable of counting photons very efficiently down to a single photon level with high avalanche gain, producing pulses at very high rates with very short rise times. Due to small gain dispersions they can be used in counting photons with high quantum efficiencies, therefore they are excellent devices for charged particle tracking using small diameter scintillating plastic fibers. In this paper, fiber tracking for the CDF and D0 upgrades and a possible usage of the VLPC readout for the experiment E803 at Fermilab will be discussed.

1 Introduction

Collider experiments and some fixed target experiments that are to run in the near future necessitate tracking systems that can take very high particle rates at high multiplicities. The Fermilab collider experiments, CDF and D0, may be running in a few years at a luminosity of 2 x 10^{32} cm^{-2} sec^{-1} with a bunch crossing time of 132 nsec or 396 nsec. Some of the exotic events like $t\bar{t}$ decay may produce hundreds of charged particle tracks with the inclusion of several underlying minimum bias events. This requires tracking with low occupancy per track sensing element. Small diameter scintillating fiber tracking would do very well for high luminosity and or high rate fixed target tracking especially for high multiplicity events. Using the speed of light in the scintillating fibers together with the Visible Light Photon Counters (VLPC) we can build a tracking system that would work for the above mentioned circumstances. The VLPC development is an important breakthrough for charged particle tracking of High Energy Particle Physics experiments that require a fast response with a high avalanche gain and with high quantum efficiency.

For comparison the fiber tracking which was built for the UA2 experiment used image intensifier readout with vacuum photocathode, and was not an efficient tracker[3] due to the relatively low quantum efficiency compared with the VLPC readout.

2 Historical Perspective

Dr. Michael Petroff (Rockwell International Science Center) and I started the joint research on fiber tracking in 1988 using a few channels of Solid State Photomultipliers (SSPMs)[1] with the support of UCLA/DOE. We used a couple of scintillating fibers of 250 micron thickness that included the PMMA cladding. The results were very encouraging, so we proposed to develop the VLPCs. The VLPCs were to be optimized for visible light with wavelengths around 500 nm and with greatly reduced sensitivity to infrared (IR) photons. The research was mainly carried out at UCLA with the support from the Department of Energy during the early years[2]. Later more institutions joined the research and development effort[4]. The results showed that the VLPC was a reality, and it could reach quantum efficiencies about 60 percent, and the sensitivity to IR could be made less than 2 percent. We did show the proof of principle that plastic scintillating fiber tracking can be a very efficient fast tracker.

In the last couple of years Fermilab has been supporting fiber tracking development for the future high luminosity collider runs of CDF and D0 after the main injector upgrade. The luminosities are expected to reach 2 x 10^{32} cm^{-2} sec^{-1} sometime after the upgrade. Continuing the R&D, the D0 group has done a Cosmic-ray test with more than 3,000 channels of VLPCs with success[5].

3 Visible Light Photon Counters

The operating principles of the VLPCs are given in Ref. 2, therefore they will be briefly discussed here. The VLPCs are Impurity Band Conduction (IBC) devices that are minimized in quantum efficiency in the infrared (IR) region while maximized in the quantum efficiency for the wavelengths around 550 nm relative to the original device, Solid State Photomultiplier (SSPM)[6], which was discovered by Rockwell International Science Center.

A schematic diagram of a VLPC is shown in Fig. 1. In a VLPC a neutral donor is a substitutional ion with an electron bound to it in a hydrogen-like orbit with an ionization potential of about 0.05 eV. Because of this very small energy gap the devices need to run at cryogenic temperatures. Nominally they run at a temperature between 6 and 7 K. When the concentration of impurities is sufficiently high they form an energy band separated from the conduction band by the ionization potential. When the applied electric field is sufficiently high, about 2 x 10^3-10^4 V/cm, each initial electron starts an avalanche of free electrons within 1 ns. The avalanche size could reach up to 5 x 10^4 when applied bias voltage reaches -7 volts. The avalanche may occupy about a 10 micron area for about 1 microsec while the rest of the area is continuously available for detecting photons. The gain and the quantum efficiency of the devices taken from same wafer are fairly uniform[7] at a common voltage and temperature as seen in fig. 2. For this an LED illuminated the VLPCs with a reasonably uniform photon flux. The sensitive area of the devices was 1 mm in diameter. Fig. 3 shows an optimized quantum efficiency (QE) curve of the devices as a function of wavelength. The QE was optimized for wavelengths around 530 nm by antireflective coating of the devices.

4 Applications and Results

As mentioned earlier the collider experiments at Fermilab are going to use scintillating fiber tracking for the high luminosity upgrade. Fig. 4 shows the planned fiber tracking region of CDF where there will be about 60,000 fiber and VLPC channels. Optical clear fibers (not shown in the figure) carry the photons through the End-Plug out to the VLPCs located outside of the Central Detector. There will be 6 axial and 6 small angle stereo doublet layers of fibers precisely positioned on low density composite cylinders, Fig. 5. The scintillating fiber diameter is 0.5 mm of 2.2 meter length that is coupled to about 5 meter optical clear fiber of 0.7 mm diameter to carry the photons to the VLPC which is outside of the central part of the CDF. The fiber tracker extends the track reconstruction capability to large rapidity, helps remove ambiguities in the silicon strip vertex tracker, and connects the tracks to the outer tracking system[8]. The Intermediate Fiber Tracking (IFT) group has reconstructed Top-Quark Monte Carlo events using the above proposed fiber tracker[9]. A typical event of a top + 6 minimum bias event in the R-ϕ view is shown in Fig. 6.a, and the R-Z view of the same event is shown in Fig. 6.b. As seen in the figure, track reconstruction efficiency is excellent owing to the high multi-track resolution of the fiber tracking system. Even the tracks in jets are not missed.

The D0 group is planning to use more fibers than the CDF group and heavily involved in the design of the VLPC-cryogenic system at Fermilab. The group has put together a 3,000 channel fiber-VLPC test system and has taken Cosmic-ray data for over a year. They obtained very encouraging results. Fig. 7 shows a resolution distribution from a staggered doublet of 0.83 mm diameter 3HF fibers. Corrected for the track errors this residual distribution would represent a sigma rms resolution better than 120 microns. Notice that the distribution is very symmetric and shows no tail[5].

Another Fermilab experiment, E803/COSMOS, could use scintillating fiber tracking downstream of the nuclear emulsion stacks to precisely locate tau-neutrino event tracks, tagging them to help find the tracks in the emulsion layers. Because this is done in real time using the VLPC readout, it would provide alignment parameters using background muon tracks. For this application VLPC readout can provide a very efficient tracking system with spatial resolution around 100 microns, and excellent multitrack resolution. Fig. 8 shows a proposed schematic drawing of the front end of COSMOS. The UCLA group has proposed this and is working on the project[10].

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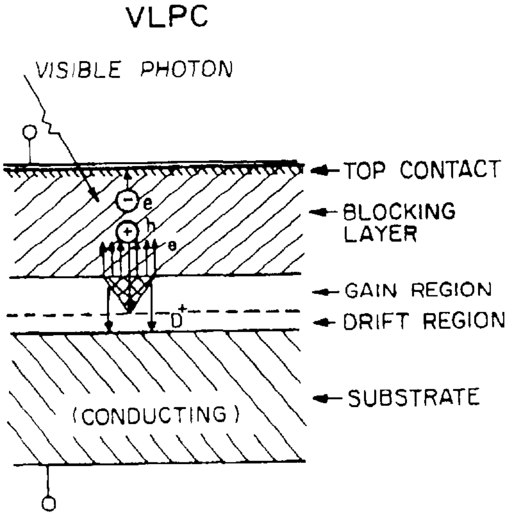

Figure 1: Schematic of the operational principles of the VLPC.

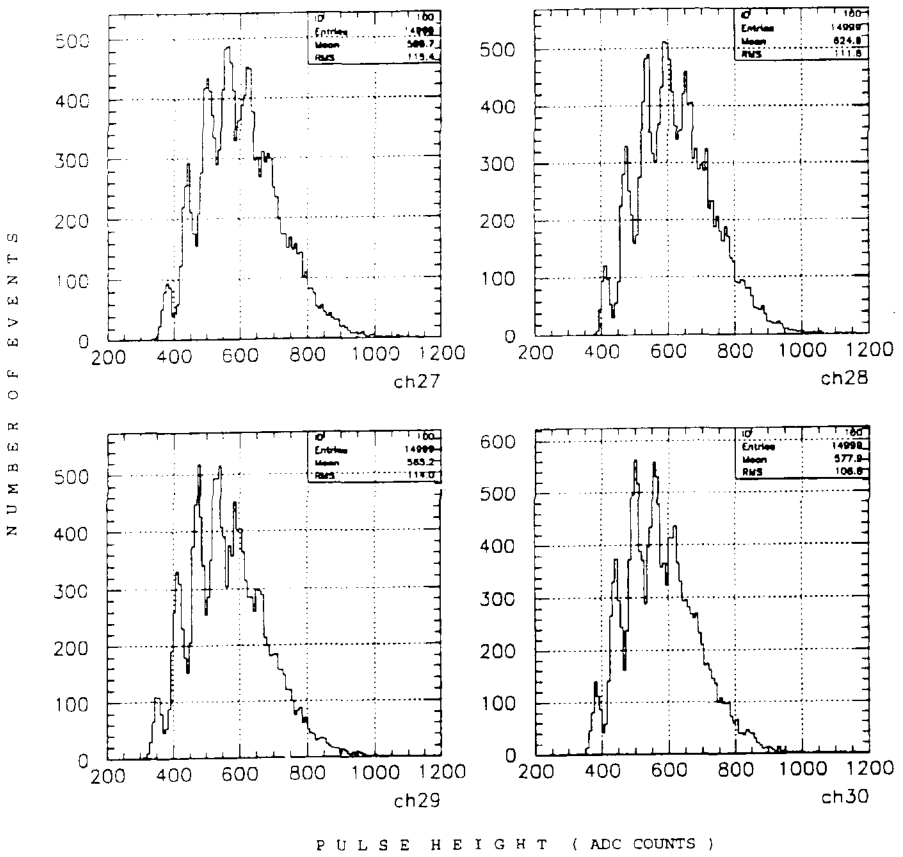

Fig 2 : Multiple photoelectron peaks resulted in when the VLPCs were illuminated with a pulsed LED. It shows that uniform respones in quantum efficiency and gain from different channels obtainable under the same bias voltage and temperature.

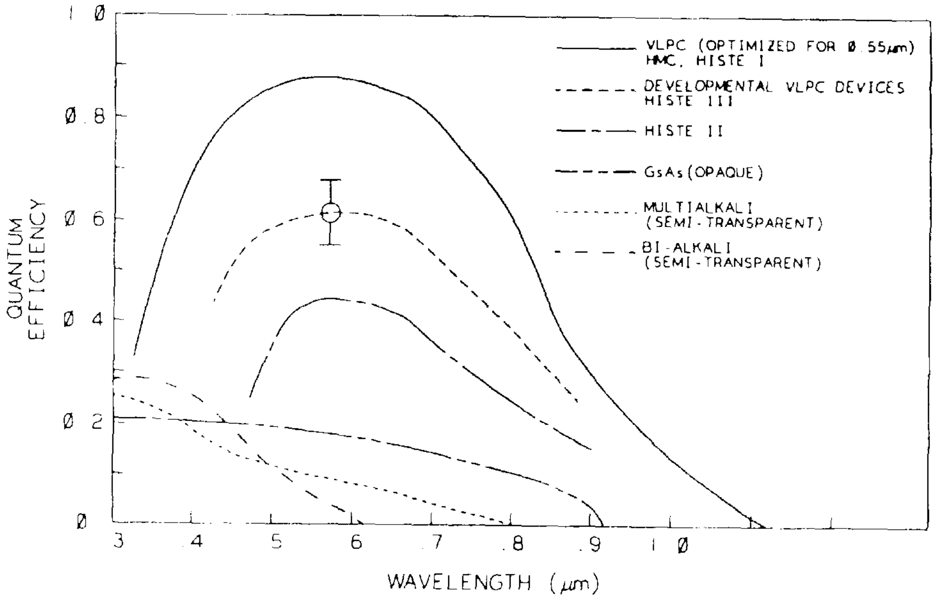

Fig. 3 : **Quantum efficiencies of the VLPCs as they were developed. It also shows the quantum efficiencies of vacuum photomultipliers in comparison.**

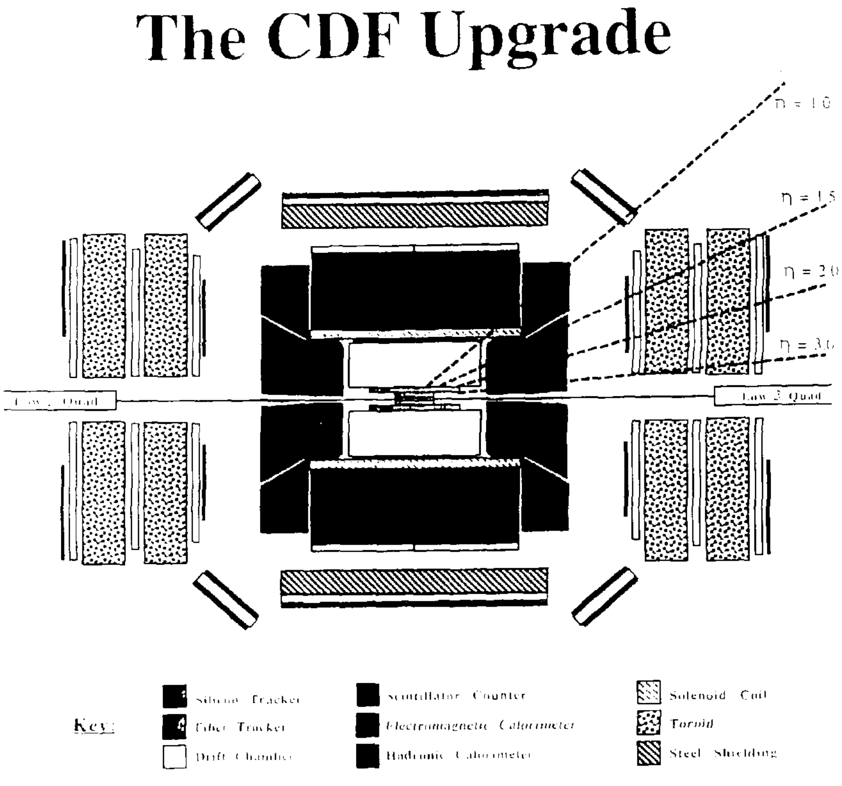

Fig 4 : CDF upgrade with fiber tracker. More details are shown in Fig. 5.

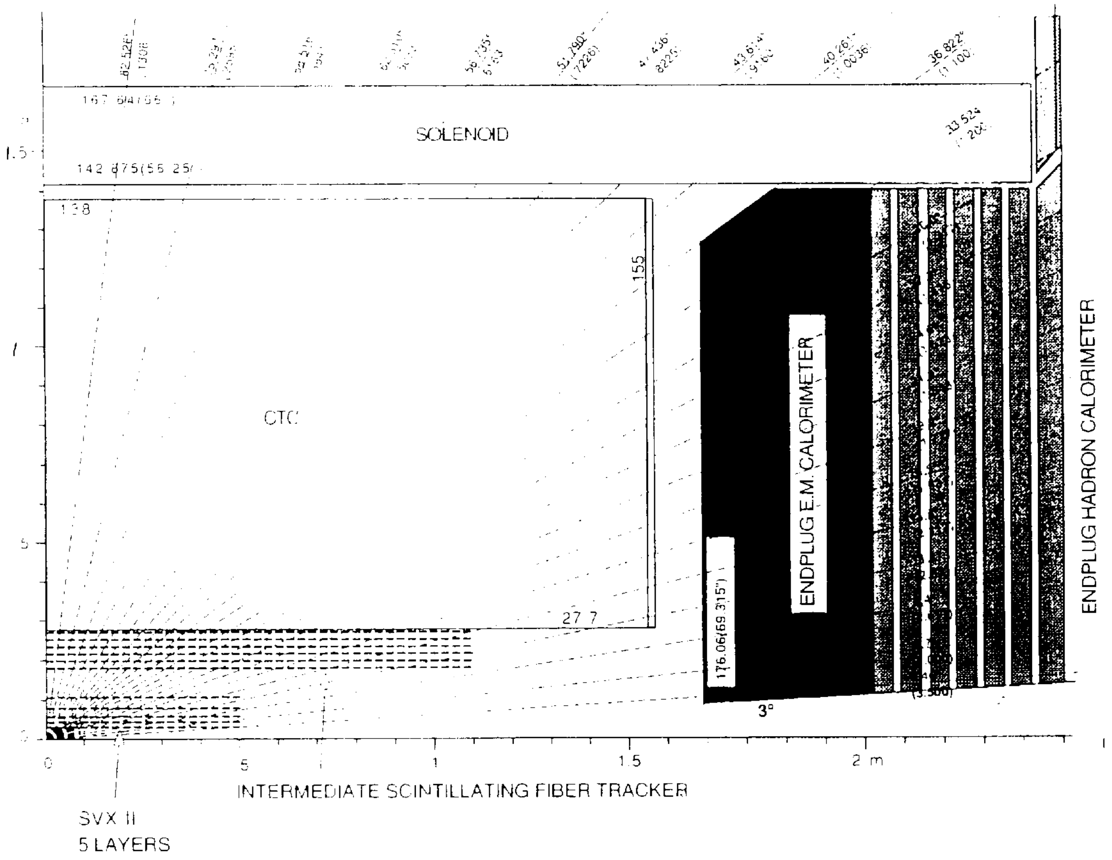

Fig. 5 : Cross-sectional diagram of the CDF tracking with the end plug. The fiber tracker will play an important role in this design.

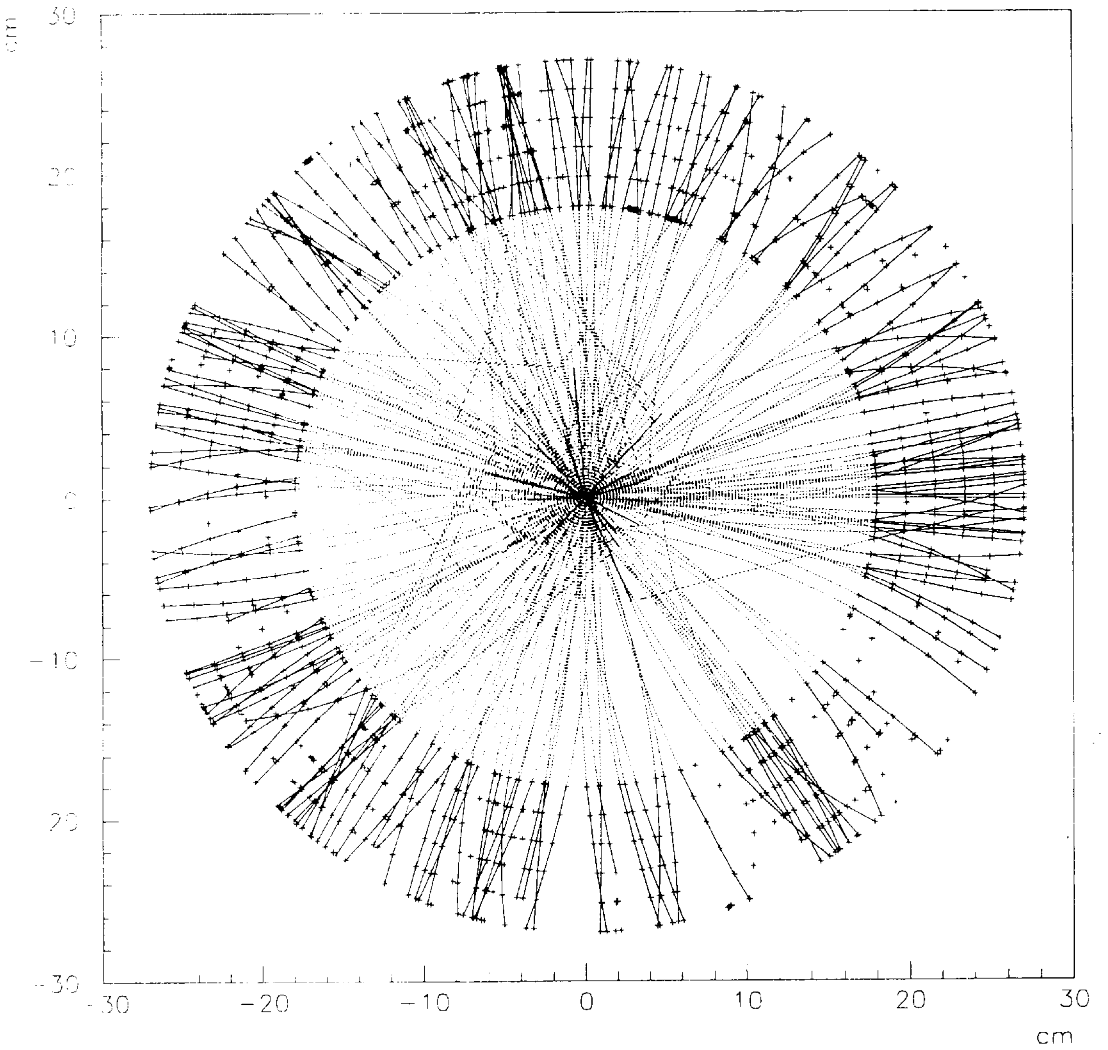

Fig.6.a :A typical top + 6 MB event in the R-ϕ view. Crosses are axial hits, solid lines connect hits used, and dotted curves are extrapolation inward of the fitted track parameters.

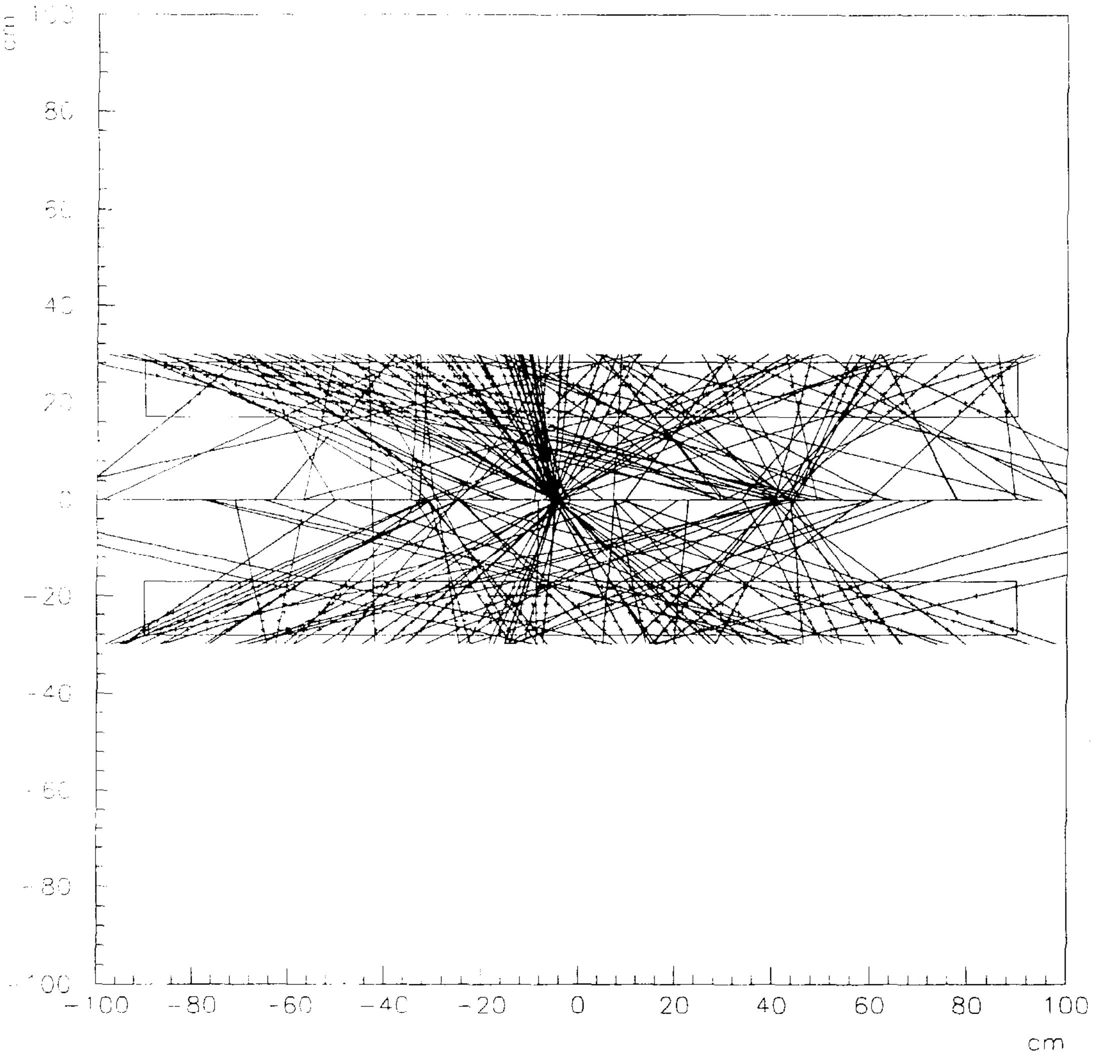

Fig.6.b : R-Z view of a top + 6 MB event. Crosses show locations of associated stereo-hit/axial-segment points. Lines show extrapolation of fitted segment to beam line.

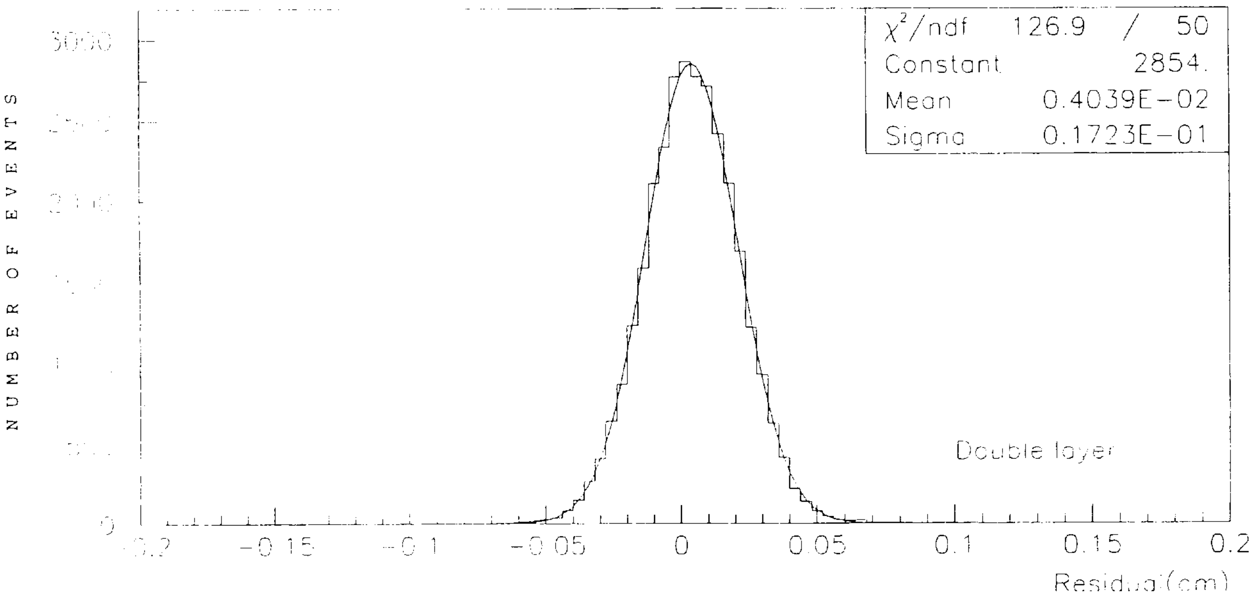

Fig. 7 : Residuals distribution from staggered doublets using Cosmic muons by the D0 group.

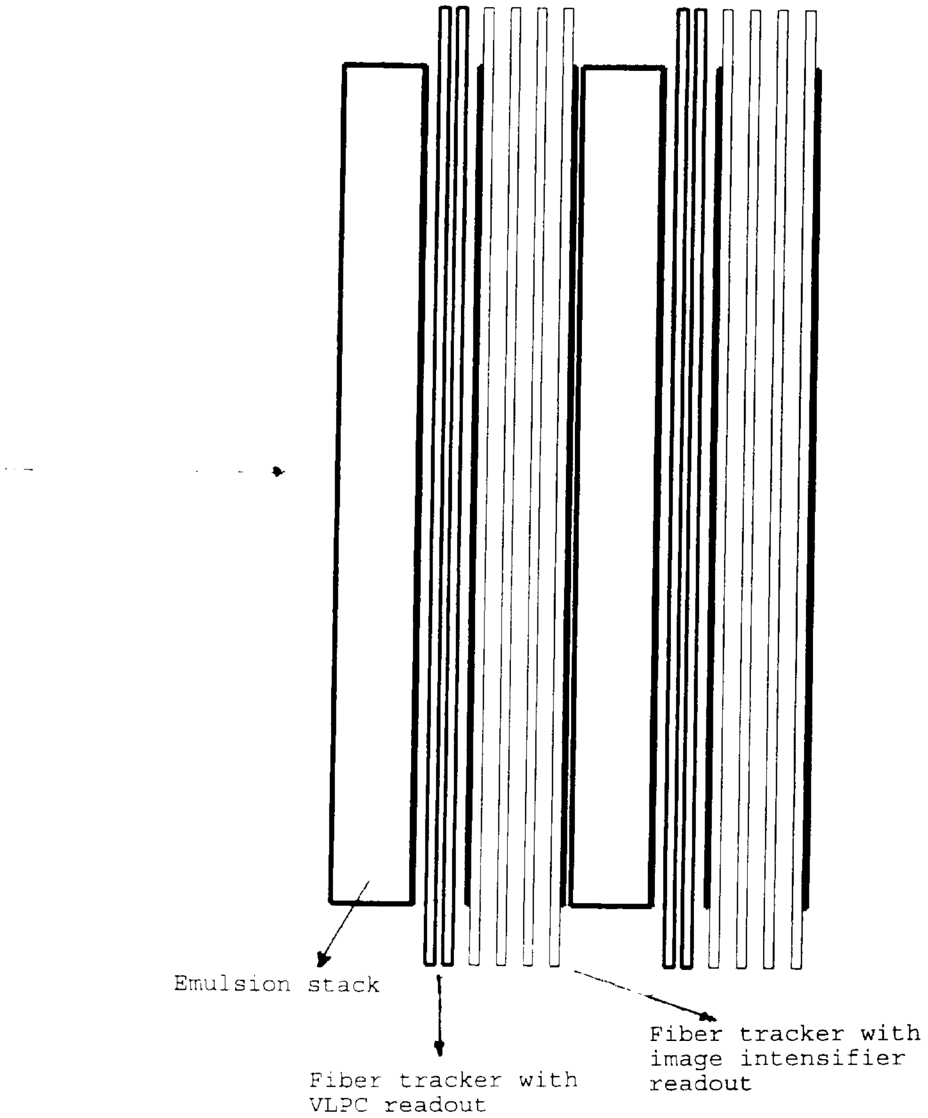

Fig. 8 : Proposed front end tracking system of E-803 / COSMOS experiment at Fermilab.