Monte Carlo Studies of a Novel LiF Radiator for RICH Detectors

A. Efimov, M. Artuso, Min Gao, R. Mountain, F. Muheim, Y. Mukhin, S. Playfer, and S. Stone

Dept. of Physics, Syracuse Univ., Syracuse, NY, 13244-1130

We show that a multifaceted LiF radiator produces more Cherenkov light and has better resolution per photon than a flat radiator slab when used in a ring imaging Cherenkov counter. Such a system is being considered for the CLEO III upgrade.

I. Introduction

Ring imaging Cherenkov detectors (RICH) are capable of providing excellent identification of charged particles. Several systems have been implemented in hadron beams and e^+e^- collider experiments [1]. Many of these have used liquid or gaseous freon radiators and have used TMAE vapor as the photosensitive element [2]. TMAE introduces special problems. Its relatively low vapor pressure requires a rather thick conversion volume ($\approx$10 cm) or high temperatures. Also, it is very corrosive, so that special handling precautions must be taken and there is evidence that it harms wire chambers.

A triethylamine (TEA) methane mixture is known to have usable quantum efficiency in the wavelength range between 135-165 nm. Liquid Freon radiators are not transparent in this wavelength region so a crystal radiator must be used. A RICH system with a LiF radiator and photon detector consisting of CH_4 and TEA vapor has been successfully tested by the Fast-RICH group at CERN [3]. With a prototype detector employing fast VLSI electronics, an average of 10.4 photoelectrons were detected, for an incident track angle of 25^o with respect to the radiator, with a resulting resolution per track of 4.2 mrad. The angle of Cherenkov radiation emitted by a charged track passing through the LiF is given by

$$cos(\theta_C) = 1/(n \cdot \beta), \quad (1)$$

where $\beta = v/c$.

We use as a benchmark the separation between pions and kaons at a momentum of 2.8 GeV/c, which is the upper limit of particle momentum from B decays from the $\Upsilon(4S)$ resonance at a symmetric e^+e^- collider. Since LiF has an index of 1.5 at 150 nm, which is the center of the useful wavelength range in this system, the K/π separation at 2.8 GeV/c is 12.8 mrad. We define separation in terms of the number of standard deviations as

$$N_\sigma = \frac{\theta_C(K) - \theta_C(\pi)}{\frac{1}{2}[\sigma(K) + \sigma(\pi)]}, \tag{2}$$

where σ refers to the rms error on the track angle measurement. The CERN test results correspond to an N_σ of 3. While a device built with this resolution would give respectable results, our goal is to design a device where N_σ equals 4.

II. Flat Radiator Configuration

The detector we envision for the CLEO III upgrade fits between the CsI electromagnetic calorimeter and a new drift chamber [4]. It is approximately cylindrically symmetric with the LiF radiators in the form of tiles ($\approx$16x16 cm^2) at an inner radius of 82 cm and a gap of 16 cm between the radiator and the entrance window of the wire proportional chamber. The length of the radiators is 234 cm, while the photon detectors are 250 cm long. The photon detector is similar to that used in the CERN tests, but differs because the pads are 7.5 x 7.5 mm^2, and the pulse height on each pad is measured.

A reasonable extrapolation of the Fast-RICH prototype results shows that the photoelectron yield can be increased by 43%. This results from several factors: increase in the size of the detector area (10%), the CERN prototype was only 50 cm wide, not sufficient to contain the full image; having the chamber voltage on the plateau (8%), only after the test was it discovered that the voltage was a bit too low; cleaner expansion volume gas (5%); thinner CaF_2 windows and strips (8%); and connecting up all of the electronics channels (5%). The quantum efficiency assumed is taken as that found in [3].

A system of flat 1 cm thick LiF radiators must have the angle of the incident charged track be larger than about 6^o with respect to the normal in order to avoid total internal reflection of all the Cherenkov light. Thus in the center of a cylindrically symmetric detector the radiators must be tilted. An angle of about 20^o is required to have adequate Cherenkov light. Even so, most of the Cherenkov light is lost.

The angular resolution per detected photon is comprised of several sources. The most important are the chromatic error, which results from the variation of the index of refraction with the wavelength, the emission point error, which results from the lack of knowledge about where the photon is emitted, and the position error in detecting the photon. The individual sources of error determined by using GEANT are shown as a function of the track dip angle θ in Fig. 1. All calculations in this paper are done using 2.8 GeV/c pions.

This system has about 13.5-14 mrad resolution per detected photon independent of the track incident angle. This corresponds to a 3.7 mrad resolution per track. The remaining calculations in this paper, however, assume a 20% degredation in

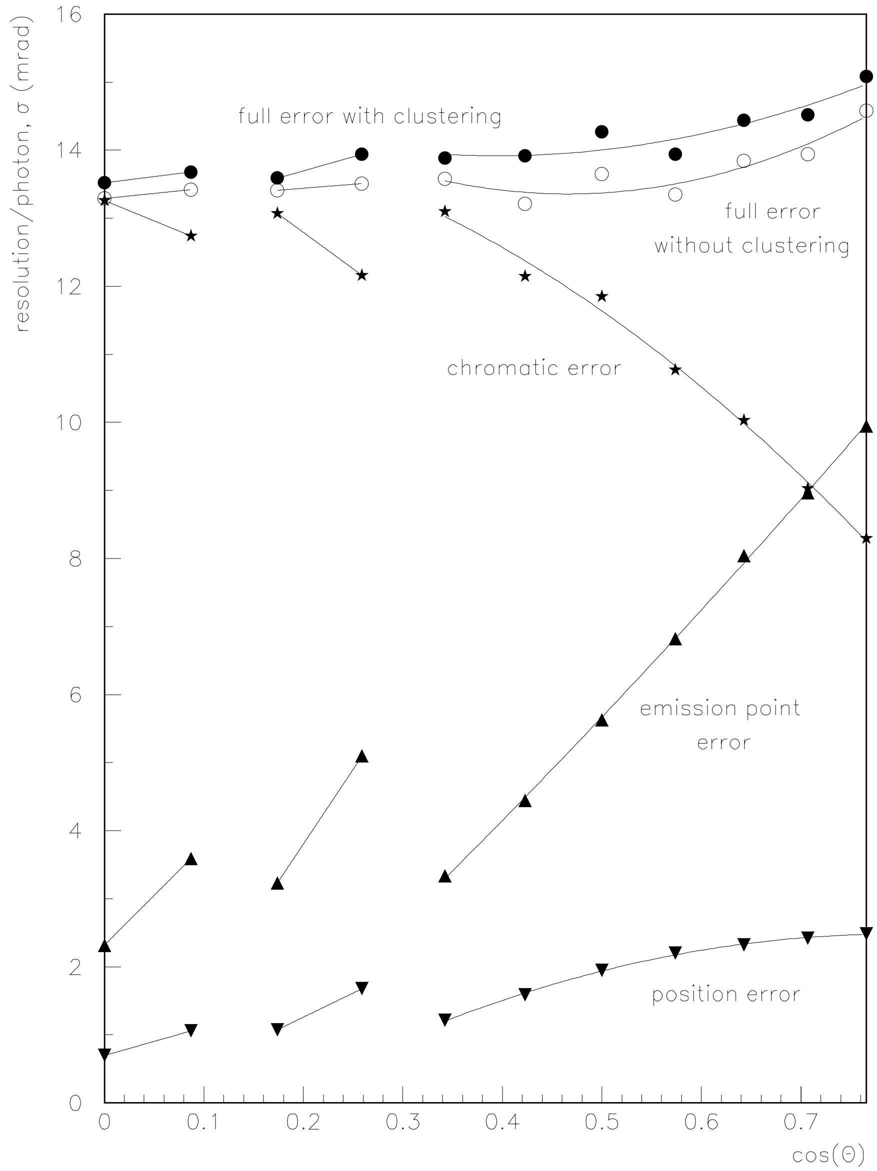

Figure 1: The individual sources of Cherenkov angle error per detected photon for a 10 mm thick flat LiF radiator. These include position determination error in the chamber, photon emission point error, chromatic error and overlap error due to some of the photons overlapping in the chamber. The breaks in the curves occur because the first two radiator sections are tilted at a 20^o angle with respect to the incident track direction.

photoelectron yield, which gives about 4.1 mrad resolution per track for the plane radiator.

III. "Sawtooth" Radiator Configuration

To get more light out of the LiF it is advantageous to facet the surface where the Cherenkov light exits. Two radiator designs with 45^0 facets which we are considering are shown in Fig. 2. The first design has 5 mm deep facets, while the second has facets of 1 mm depth. The grooves run along the 234 cm length of the detector, i.e. along the z-axis. To explore the potential of such radiators, we performed Monte Carlo simulations of different facet angles always keeping the average thickness of the radiator at 10 mm. Although we have simulated both radiators, we show results only for the more shallowly faceted one. The smaller facets give somewhat better performance in that the spread in thickness of the radiator is much smaller. Quantities of interest are the angular resolution per photoelectron, the average number of photoelectrons, the resolution per track and the probability of pions faking kaons. The angular resolution per photon changes because of differences in the chromatic error, which is influenced by the angle of the photon with respect to the normal as it leaves the surface [5].

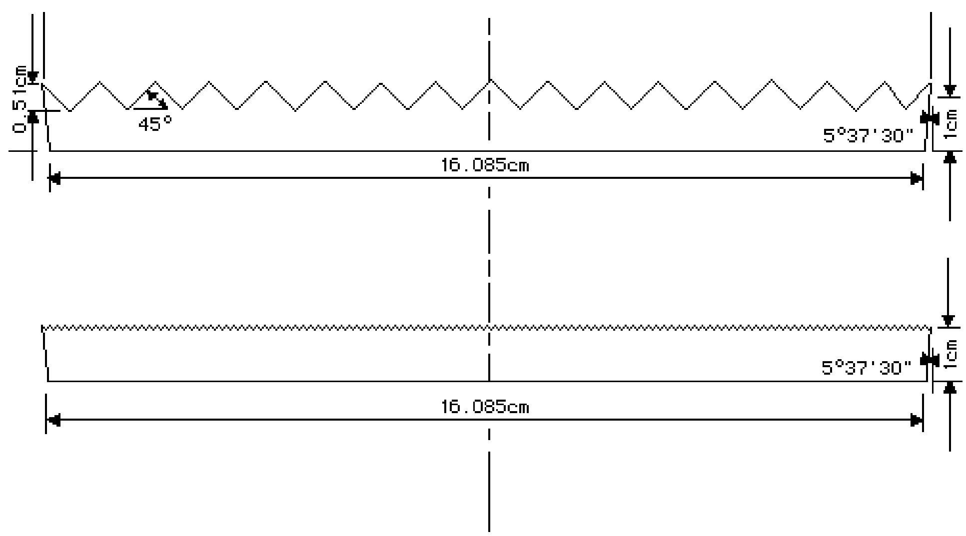

Figure 2: Two possible "sawtooth" designs. The bottom one has groves of 1 mm depth.

In order to compare different facet angles expeditiously, we did not use a full GEANT simulation, as we removed multiple scattering and hadronic interactions. In Fig. 3 we show the average number of detected photoelectrons as a function of incident track angle, $cos\theta$, for different teeth angles, where larger angles refer to sharper teeth. In order to more closely simulate the actually detector geometry, with a fixed length photon detector, we included mirrored ends with a reflectivity of 80% at 150 nm. Also shown is the flat radiator for the non-tilted sections. The optimum angle is close to 45^o. (Note, the Cherenkov angle is 48^0 for relativistic tracks.)

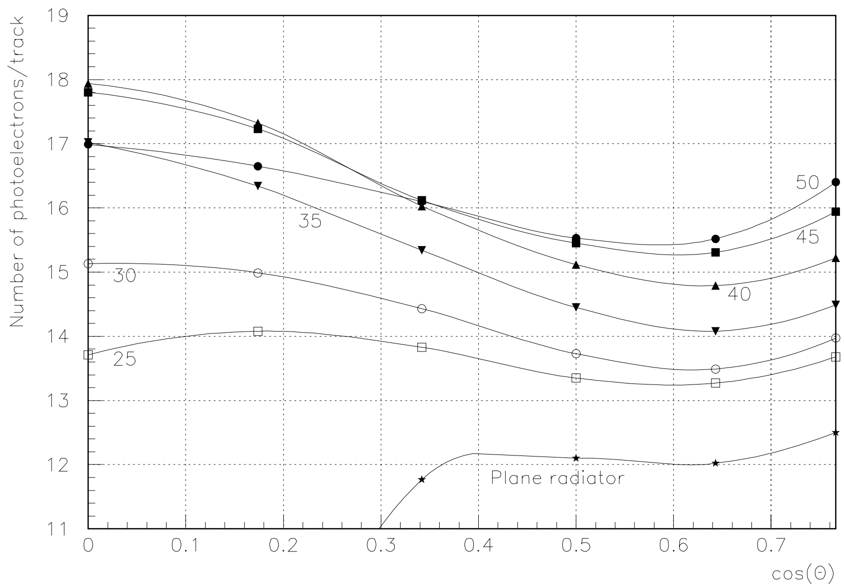

Figure 3: The average number of photoelectrons detected as a function incident track angle for different "tooth" angles. The expected photon yield has been degraded by 20%.

In Fig. 4 we show the resolution per photoelectron. Also here the optimum angle is close to 45^o. The angular resolution per track is shown in Fig. 5. Although the

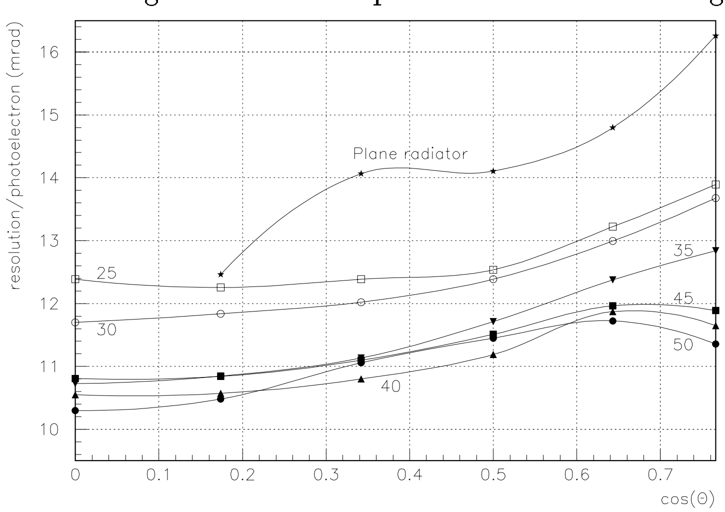

Figure 4: The angular resolution per photon as a function of incident track angle for different "tooth" angles.

angular resolution typically characterizes the detector performance the image of the photoelectrons here has a complicated shape. In Fig. 6 we show the light pattern for a track normal to the radiator, for a 45^o tooth angle. Recall, that for a flat plane radiator no light exits from radiator surface. The image consists of two intense hyperbolas resulting from light which directly exits the radiator surface, and two lightly populated hyperbolas which result from photons which experience one reflection from the sawtooth surface, either before or after exiting from the surface. There is only ≈6% of the light in these more extended curves.

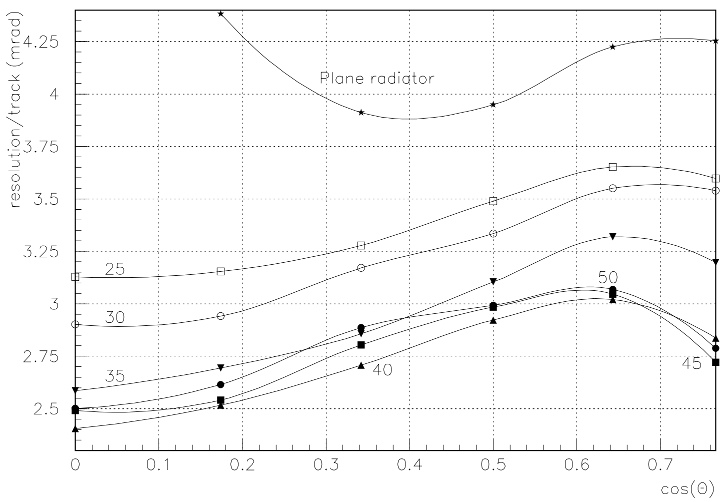

Figure 5: The angular resolution per track as a function of incident track angle for different "tooth" angles. The expected photon yield has been degraded by 20%.

This complex pattern causes the fake rate to be somewhat larger than what would be implied by the angular resolution per track and the difference in Cherenkov angle between different particle species, especially at large values of $cos\theta$. In Fig. 7 we show the probability for pions to fake kaons at momentum of 2.8 GeV/c as a function of $cos\theta$, for a 95% efficiency for the pions. It is possible that the algorithm that assigns the hits to a particular section of pattern with a particlular weight can be improved. We also show the fake rate for a plane 1 cm thick radiator. The sawtooth has less of an advantage at large $cos\theta$, but is still better than the plane radiator.

Combining these considerations, we find that the best performance in terms of lowest fake rates is given by 45^o teeth.

We proceed by performing full GEANT level simulations on the 45^o tooth angle radiator. The resolution per photoelectron, the number of photoelectrons and the Cherenkov angular resolution per track for θ equals 90^o is shown on Fig. 8.

We see a large average number of photoelectrons. The spread in this distribution is not widened appreciably by the variation in LiF thickness from 9.5 to 10.5 mm. For these distributions we used a full GEANT simulation including clustering of the pad hits into detected photons, or photoelectrons which causes a widening of the

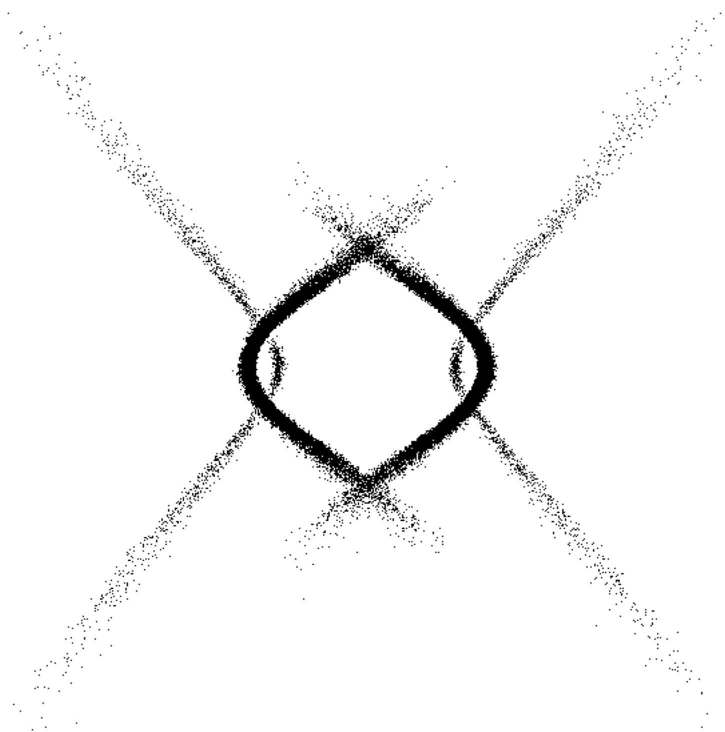

Figure 6: The image pattern for tracks normal to the radiator.

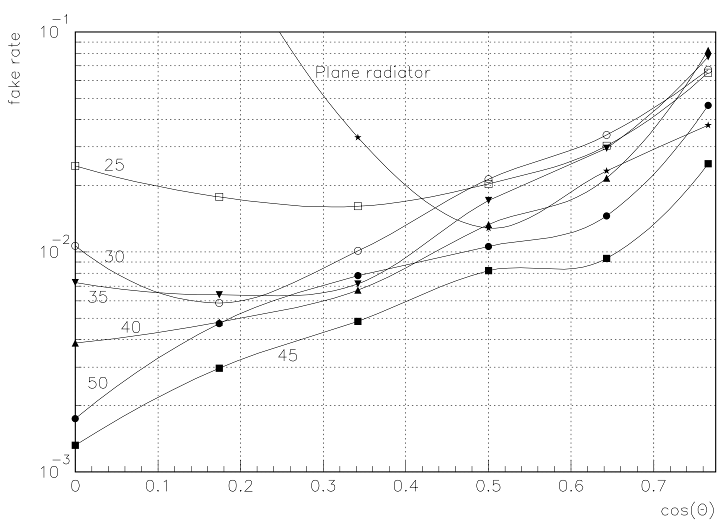

Figure 7: The probability for a 2.8 GeV/c pion to fake a kaon, for 95% pion efficiency, as a function of incident track angle for different “tooth” angles.

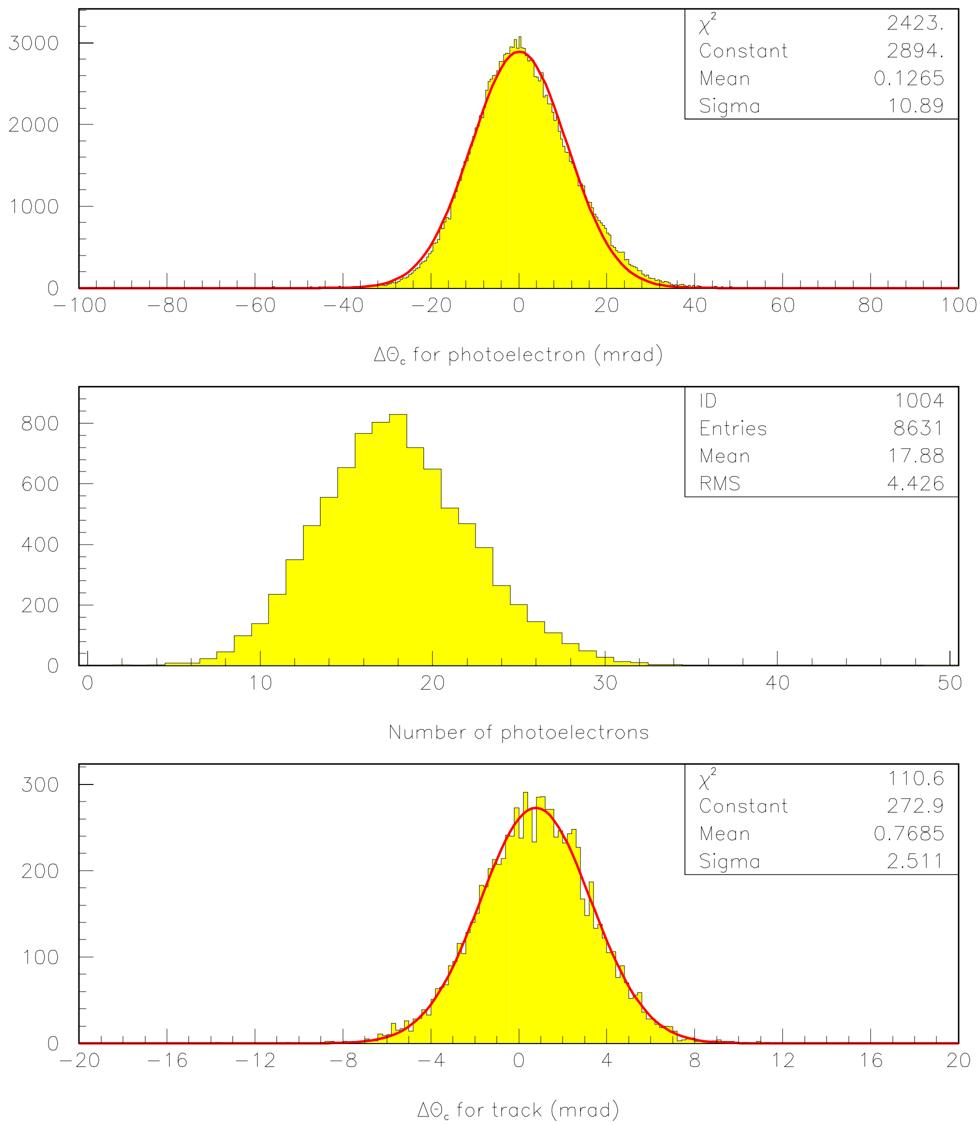

Figure 8: The resolution per photoelectron, number of photoelectrons and Cherenkov angular resolution per track, for an incident track normal to a 45^o sawtooth radiator.

resolution. The clustering may be ameliorated with better software algorithms. The resulting 2.5 mrad resolution has been obtained assuming a 20% loss of light caused by the geometric shape of the sawtooth due to the corners or the surface polish. This is much better than the projection using the plane radiator of 3.7 mrad, where the 20% light loss has not been applied. The number of photoelectrons, before and after clustering, is shown in Fig. 9 as a function of $cos\theta$.

Tolerances in the manufacture of grooved radiator structures are important. The amount the resolution will worsen if the flat edges of the grooves are not parallel depends on the groove depth, since deeper grooves have more photons from a given track exiting through one surface. If all the photons exited through a single groove the grooves need to be parallel to angle small compared to the resolution, something like ± 0.5 mrad. For shallow grooves the photons sample many grooves and the requirement loosens to ± 3 mrad. Each groove also needs to be flat to ± 3 mrad (rms) along its length. The groove depth can vary as this dimension is not critical. We are working with samples machined by the Center for Optics Manufacturing [6] using material from OPTOVAC [7].

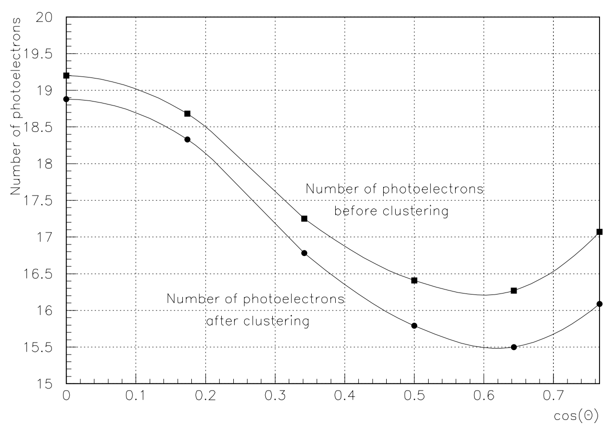

Figure 9: The number of photoelectrons hiting the detector (before clustering) and the number reconstructed by the pattern recognition program (after clustering) as a function of the incident track angle.

IV. Conclusions

Simulations have shown that a multifacted radiator with 45° teeth gives substantially more photons, better angular resolution per photon, and lower fake rates than plane crystal radiators. The fake rates predicted using a full GEANT simulation for different radiators are summarized in Fig. 10, for plane and sawtooth radiators of different thickness. A thinner plane radiator does better at large $cos\theta$ because the emission point error is the largest source of error in this region.

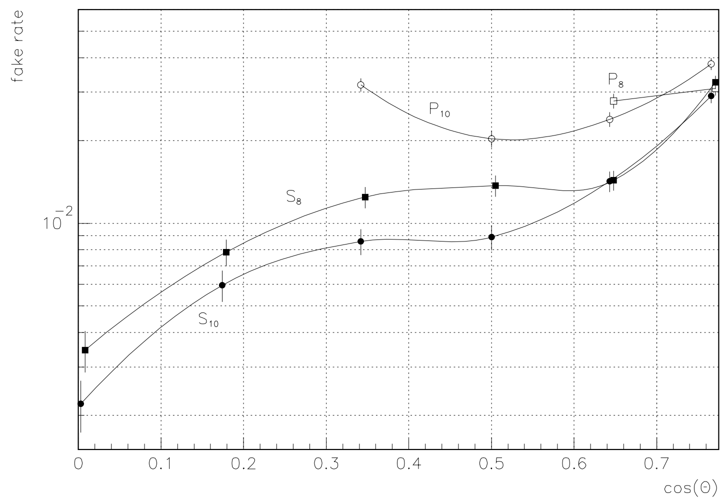

Figure 10: The fake rates at 95% efficiency from a full GEANT simulation of different radiators of different thicknesses. P_8 and P_{10} denote plane radiators of 8 mm and 10 mm thickness, while S_8 and S_{10} denote sawtooth radiators of average thickness of 8 mm and 10 mm, with 1 mm deep 45^o grooves. A light yield of 80% of that projected has been assumed.

References

[1] J. Seguinot and T. Ypsilantis, Nucl. Instr. & Meth. **A343**, 1 (1994).

[2] W. Adam et al., (DELPHI), Nucl. Instr. & Meth. **A343**, 68 (1994); K. Abe et al., (SLD) Nucl. Instr. & Meth. **A343**, 74 (1994); R. Baur et al., (CERES) Nucl. Instr. & Meth. **A343**, 87 (1994); H.-W. Siebert et al., (Omega) Nucl. Instr. & Meth. **A343**, 60 (1994).

[3] J. Seguinot et al., "Beam Tests of a Fast-Rich Prototype with VLSI Readout Electronics," CERN-PPE/94-94, to be published in Nucl. Instr. & Meth. (1994).

[4] "The CLEO III Detector Design and Physics Goals," CLNS94/1277 (1994).

[5] T. Ypsilantis and J. Seguinot, Nucl. Instr. & Meth. **A343**, 30 (1994).

[6] We thank Don Golini of the Center of Optics Manufacturing (COM), Univ. of Rochester, Rochester, N. Y.

[7] OPTOVAC in North Brookfield Mass. supplied the LiF crystal for the CERN tests, is supplying the material for the COM tests and is working with us on studies of polishing and testing the grooved radiators.