RICH Note 7
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Studies of the Ultraviolet Transparency of a Sawtooth Radiator

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Abstract

We have conducted several tests of a prototype LiF sawtooth radiator from OPTOVAC. This sawtooth radiators that are proposed for the CLEO III RICH, has a flat surface and 45^o "tooth" structures on the opposite surface. We describe tests to measure the quality of the polish on these surfaces in the ulrtaviolet band of λ = 135 - 165 nm, comparing the special polishing technique prepared by OPTOVAC for this unique geometry to the conventional polishing techniques used for planar crystals. The preliminary studies look very promising.

1 Introduction

This note describes some measurements of a prototype sawtooth radiator produced for us recently by OPTOVAC Corp. The sawtooth radiator is a novel geometry for our CLEO III RICH designed to increase the light output of the LiF radiators and reduce chromatic errors in the Cerenkov angle reconstruction. Its idea is described in Reference [1]. Just as for the planar LiF radiators that are under consideration for the RICH, the sawtooth radiators need to be transparent to ultraviolet light in the 135 - 165 nm wavelength range of the quantum efficiency of our photon detectors, or else the Cerenkov light won't get out of the radiator and into the detectors. The geometry of the first sawtooth radiator prototype from OPTOVAC is shown in Figure 1(b).

Because of the unusual geometry of the sawtooth, it is difficult to provide a good polish on the tooth surfaces, particularly in the VUV. Conventional lap polishing techniques are suitable only for planar crystal surfaces. OPTOVAC has developed a "linear polishing" technique that allows them to reach down into the tooth grooves and polish very near the whole surface to the bottom. For this first prototype of a sawtooth radiator, OPTOVAC had to make 42^o tooth angles in order to get as close to the bottom as possible with the polishing tool, and the crystal had to be picked up and rotated to cut and polish the 2nd face of each tooth. We expect this procedure to improve once OPTOVAC obtains and employs an "SX" optical-quality CNC milling machine for the sawtooth cutting, but for the present prototype crystal these facts will mean that the polish may not be uniform from tooth to tooth and may mean that the polish will not extend uniformly into the bottom of the valleys.

The tests we did aimed at investigating (i) the transmission of the tooth surfaces relative to a 45^o LiF prism that was polished with the conventional lap technique (see

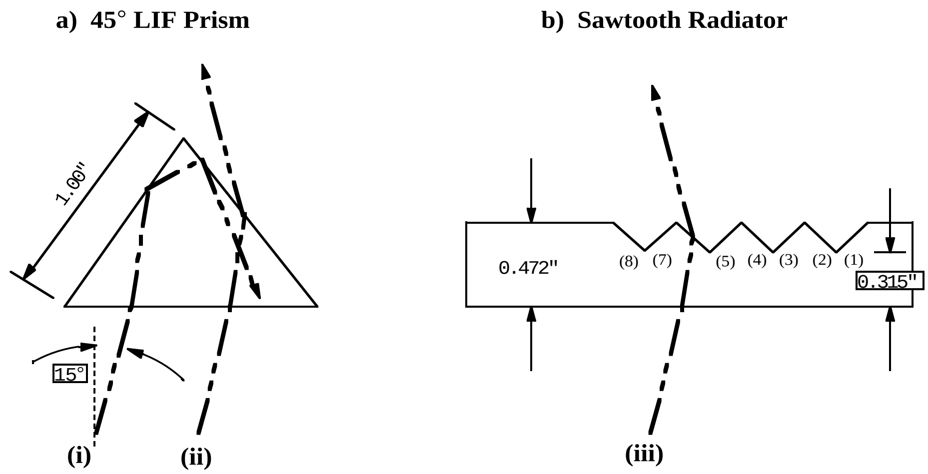

Figure 1: Schematic view of the sawtooth measurements. (a) a light beam is impinged upon a 45^o LiF prism at an angle off of the normal. Note that light beam (i) is totally internally reflected while (ii) is not and gets out to the detector. (b) the same light beam is then impinged upon the flat surface of the sawtooth radiator. The light output in (b) is normalized to the light output in (a) to give a relative measure of the transmission of the sawtooth radiator.

Fig. 1(a)) and (ii) any radii that might exist in the teeth either at the tips or in the valleys. As shown schematically in Figure 1(b), the basic idea of these tests is to send a light beam at an angle into the flat side of the sawtooth, and have the light pass through a single tooth surface, where it is detected (a normally incident beam would be totally internally reflected at the 45^o edge of the crystal). This transmission is compared to a similar measurement of a LiF 45^o prism (the "reference prism"), as shown in Figure 1(a). For these measurements, the light beam cannot be normally incident upon the flat surface because it would totally internally reflect at the 45^o boundaries. We therefore send it in at angle of $\theta = 15^o$. As noted in the Figure, the light beam has to be aimed "into" the side of the tooth or prism to be measured; that is, light beams (ii) and (iii) are transmitted into the light detector, while beam (i) is totally internally reflected back into the crystal. So, in the measurements to be presented, the crystals are scanned with the light beam first at $\theta = +15^o$, then rescanned at $\theta = -15^o$, the sum of the two yielding a complete measurement of the crystal. The measuring appartus is described in detail in Appendix A. Basically, the crystal is mounted on an computer controlled X-Y stage which allows precise movement transverse to the beam, while a monochrometer selects light of a specfice wavelength. Except as specifically noted otherwise, all tests were performed at $\lambda = 156.8$ nm.

2 Sawtooth Tests

For the sawtooth tests, we mounted both a 1" 45^o LiF prism (L) and the sawtooth prototype sample (M) on the tray (E) which moves with the X-Y stages, as shown in Figure 2. A UV mirror (C) was sometimes used to change the beam angle.

2.1 Scans with Beam at Normal Incidence

The first test we did was to scan both the 45^o prism and the sawtooth prototype with the beam angle $\theta = 0^o$; i.e.: the mirror was withdrawn from the beam, allowing the beam to impinge upon the crystals at normal incidence. We did a crystal-in-crystal-out measurement for each crystal, so that in each case the normalization was taken to be the incident beam. In this case, we do not expect any light to get out of the 45^o surfaces on either of the two samples. Indeed, we don't see any light through the reference prism. We do see light come through the sawtooth, however, as shown in Figures 3 and 4.

In Figure 3 we see that the flat part of the sawtooth has an impressive mean transmission of 83% on one side and 86% on the other side at $\lambda = 156.8$ nm. In a previous flat tile manufactured by OPTOVAC (a 17 x 17 x 1 cm^3 piece) The average transmission is 82% at this wavelength. More recent 1 cm thick samples from the ingot produced this January for our radiator production had measurements closer to 86%. Not surprisingly, this prototype radiator was made from this more recent ingot.

In Figures 3 and 4 we see an interesting structure which correspond to the peaks and valleys of the teeth. The teeth positions, noted in Figure 4, have smaller light outputs, and the widths of these outputs are comparable to the beam width itself (0.014". See the discussion in Appendix A). Thus, one may guess that the light that is getting out at these tip positions is due to the finite width of the beam, which sometimes aims light onto the crystal at less than the Brewster angle. The valleys of the teeth, however, have more light output and the width of this region is larger (0.025"). One might guess that there is a radius at the bottom that is letting the light out in this region. Unfolding the effect of the finite beam width, we estimate that this radius at the bottom is 0.020". Also, note that the light output in the sides of the teeth is not identically zero, as it was for the prism. There seems to be a few percent light output, even though we expect the light to be totally internally reflected. This light may be due to some surface variations.

2.2 Scans with Beam at $\theta = 15^o$

To measure the transmission of the tooth faces with respect to the prism, we insert a mirror into the beam and project the light into the crystal at angle of 15^o from the normal. We first scanned the 45^o prism, and the resulting light output is shown in Figure 5. Note in this figure that one half of the prism transmits the light and the other half (to the left of the prism apex) largely does not. As excptected the narrowest part of the prism (near $x = 1.2$") is the most transmitting, while the thickest portion of the prism (near $x = 0.7$") is the least transmitting, a reflection of the bulk tranmission properties of the material. There are some irregularities in the surface evident here, such as the light that gets through near 0.5", and the apparent dip in the transmission

Figure 2: Diagram of the vacuum monochromator tank when doing a scan of the 45 reference prism and the sawtooth radiator using the deflected beam. (A) = monochromator light beam; (B) = collimating slit; (C) = VUV mirror; (D) = collimating slit; (E) = moving tray mounted on X-Y stages; (F) = sodium salicylate covered glass window; (G) = Photomultiplier tube; (H) = X axis linear stage; (J) = vacuum box's wall; (K) = Y axis linear stage; (L) = 45^o prism; (M) = sawtooth radiator.

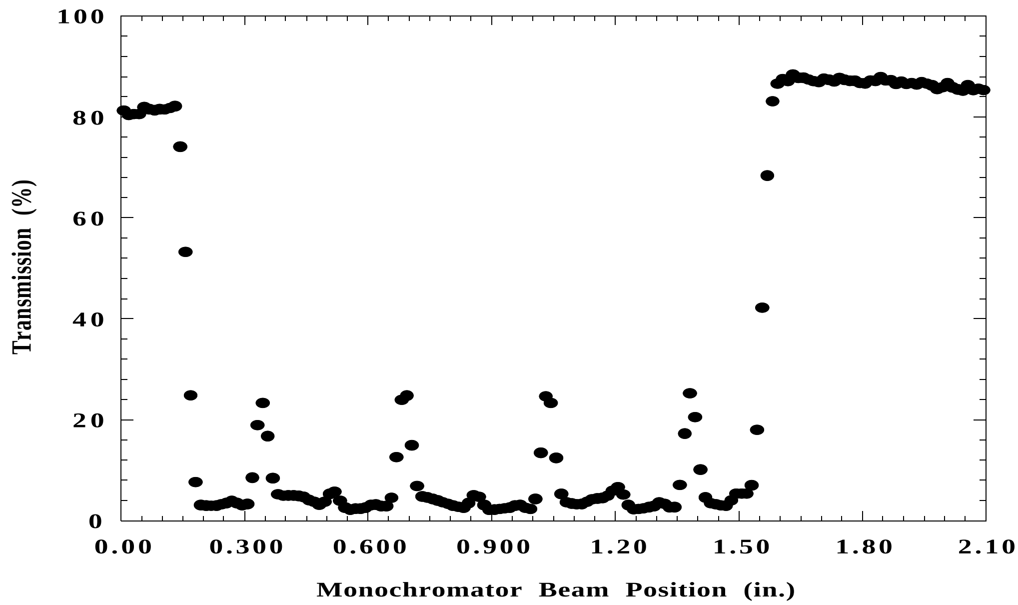

Figure 3: Scan of the sawtooth radiator with a vertical light beam (λ = 156.8 nm). Here the reference measurement is a crystal out measurement, not the 45^o prism. If we had an ideal beam and an ideal sawtooth, the flat portions of the prototype crystal would transmit and none of the 45^o surfaces would transmit light (the region between 0.25" - 1.5").

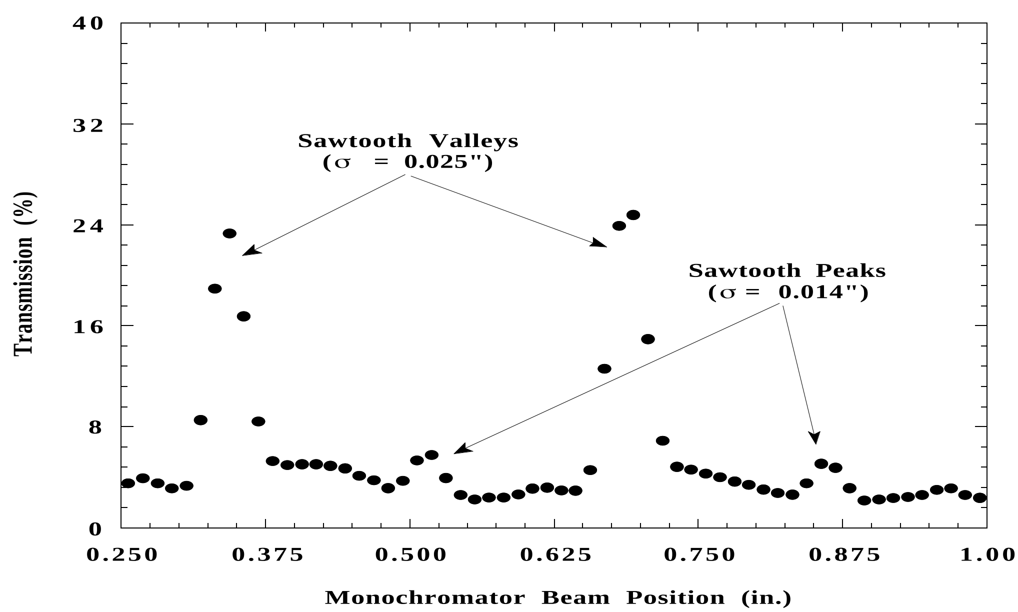

Figure 4: Close–up view of the scan of the sawtooth radiator with a vertical light beam (λ = 156.8 nm) in Figure 3. If we had an ideal beam and an ideal sawtooth, the flat portions of the prototype crystal would transmit and none of the 45^o surfaces would transmit light (the region between 0.25" - 1.5").

near 0.9"-1.0". Largely, however, the prism behaves as we expect, and we procede to use this as our reference for the sawtooth. However, assuming that the dip at 0.5" is due to a surface imperfection in the prism, we correct this spectrum to be a flat line, which means that all transmission measurements are corrected downward by 2%. This correction results in a more conservative estimate for the sawtooth transmission.

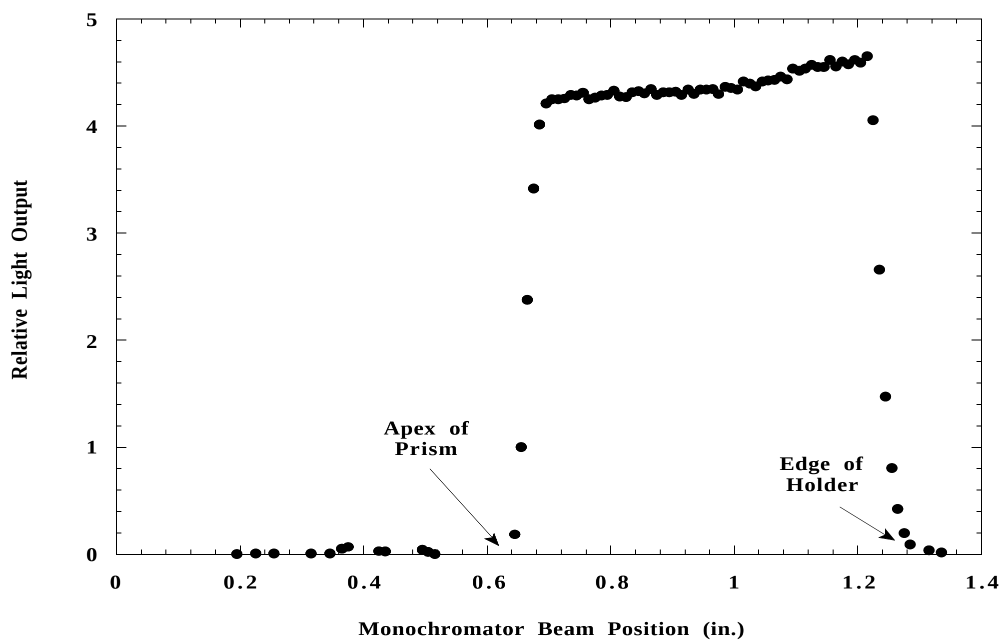

Figure 5: Light output observed through the 45^o reference prism with the beam at $\theta = +15^o$. To the right of the prism apex, we expect and observe light transmission through the 45^o surface. To the left of the apex, we expect total internal reflection of the light, and observe very little or no light whatsoever. The fall-off of the light at 1.3" is due to the opaque holder in which the prism sits. As expected, the transmission increases away from the apex, since there is less bulk material for the light to traverse.

We next scanned the sawtooth with $\theta = +15^o$, as shown in Figure 6, and again with $\theta = -15^o$, as shown in Figure 7. In the first scan we expect to get light through faces 1, 3, 5, and 7 of the teeth (as labelled in Figure 1), while in the second scan we expect to get light through faces 2, 4, 6, and 8. The reference measurement in each of these two scans was taken through the 45^o prism, where we tried to go through 1cm of material in the prism. The average transmissions of each of the teeth are listed in Table 1.

Beyond this observation, there are several details apparent in the two scans. First, that there is a 15% difference from tooth to tooth in the crystal. Second, some individual teeth have 15% variations at different points within the tooth (for example, face # 6). Third, we again are getting some small amount of light (3 - 4%) through the surfaces where we expect to see nothing. Looking at the crystal by eye, it is possible to see some variations in the surface finish. These effects may be due to such surface gradations.

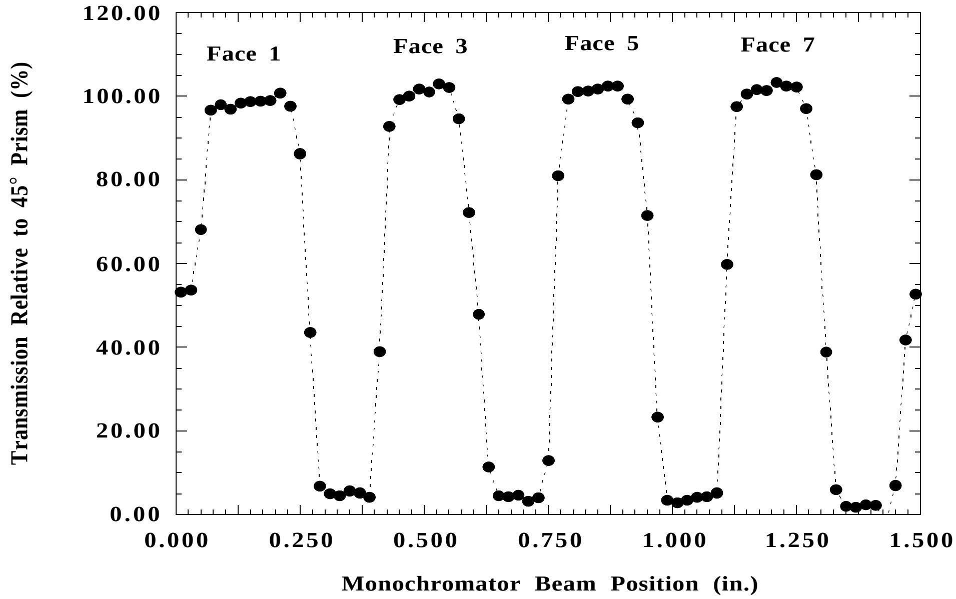

Figure 6: Scan of the light output through the prototype sawtooth radiator with $\theta = +15^o$, normalized to the light output through 1 cm of the 45^o LiF reference prism. If we had an ideal sawtooth, each tooth would be a miniature duplicate of the curve in Figure 5.

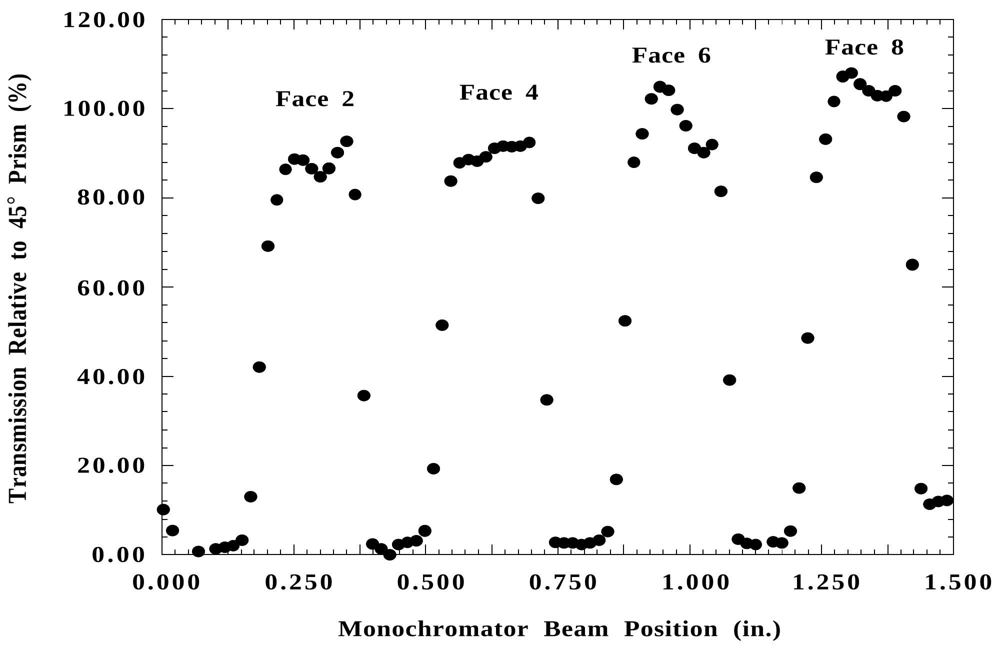

Figure 7: Scan of the light output through the prototype sawtooth radiator with $\theta = -15^o$, normalized to the light output through 1 cm of the 45^o LiF reference prism. If we had an ideal sawtooth, each tooth would be a miniature duplicate of the curve in Figure 5.

Table 1: Mean transmissions for each of the faces in the sawtooth prototype crystal (as labelled in Figure 1). In trial number 1, the entire sawtooth crystal was scanned, with a normalization point taken before and after (leaving approx. 45 min. between normalizations). In the second trial, a normalization point was taken before and after each tooth scan, leaving less possibility for drift of the reference signal.

Tooth No.	Trial 1	Trial 2
1	99%	
2	89%	89%
3	101%	
4	90%	90%
5	101%	
6	97%	98%
7	101%	
8	104%	104%

Motivated by the 3% light transmission where we expect none, we tried scanning faces 7 and 8 again, with $\theta = -15^o$, but this time we covered all the adjacent surfaces with a thin (.004" thick) teflon sheet, presumably to block any "stray light" coming out adjacent teeth (see Figure 8). As before, we see a mean transmission of 104% in face # 8, but oddly enough the formerly 3% transmission through face 7 is now observed to be zero! See Figure 9. One thought we had is that the surface quality of the adjacent tooth was poor enough to allow 3% of the totally internally reflected light out, as sketched schematically in Figure 8. Even a perfectly polished sawtooth will produce some light out when light is shone on these surfaces, just from the point of view of multiple internal reflections, so maybe these are not surprising observations.

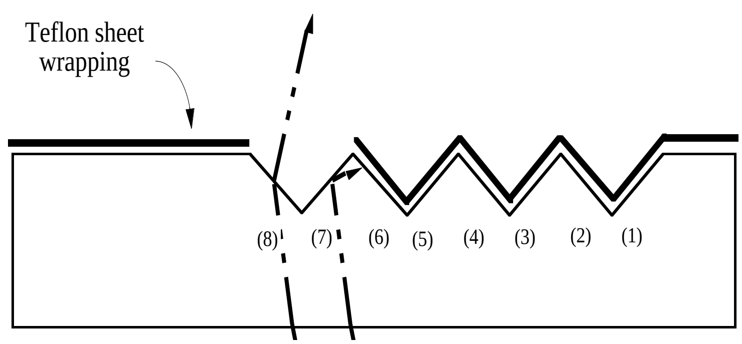

Figure 8: Schematic view of the test we did wrapping most of the teeth on the prototype with teflon (thick black lines). With the light incident at $\theta = -15^o$, light should only be transmitted through tooth surface number 8, the light through #7 being totally internally reflected.

We have also attempted to scan the whole sawtooth crystal using a 140 nm beam. The resulting scan is shown in Figure 10. This measurement is less precise because of the low light level from the monochrometer (the light output for the reference measurement was just 17 mV, and individual measurements have only $\pm$ 0.6 mV precision). Furthermore, a signal this large was attainable only because we opened up the

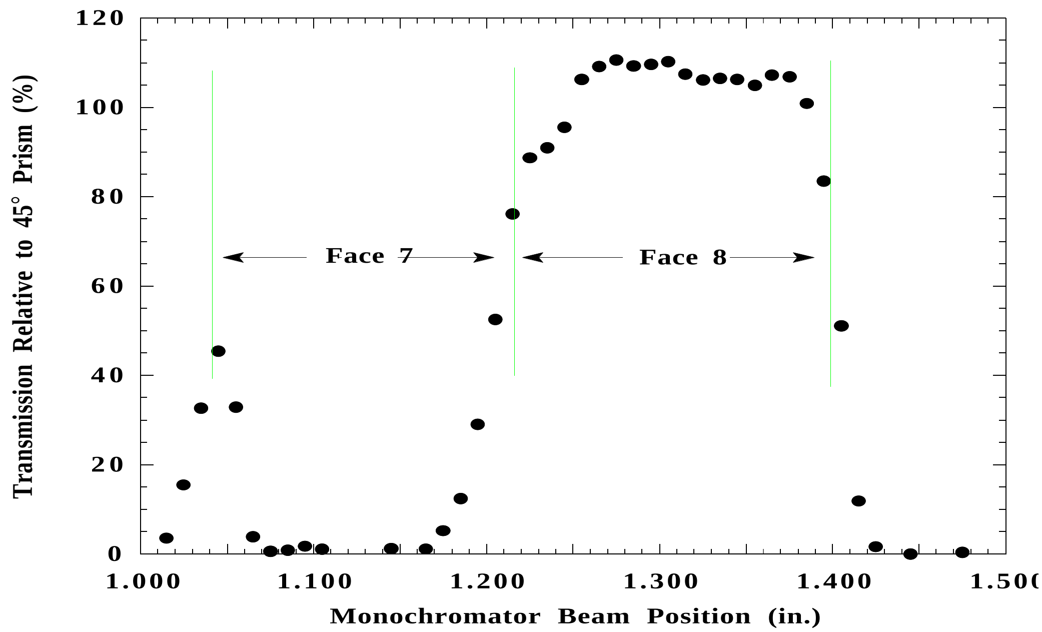

Figure 9: The results of the scan shown schematically in Figure 8. The small peak near 1.050" is due to the wrapping not covering all of tooth face # 6.

monochromator slits, which introduced backgrounds of $3-4$ mV[2]. This background has to be subtracted from the sawtooth scan and the reference measurement, resulting in the 7% normalization uncertainty (the background subtraction is even less certain than usual because the UV mirror has a wavelength-dependent reflectivity). Despite the 5% point-to-point uncertainties and the 7% overall normalization uncertainty in this plot, we can set a lower bound on the transmission of the sawtooth at 140 nm (comparing again to the 45^o reference prism).

3 Conclusions

The sawtooth prototype shows excellent transmission properites. We saw typically as good transmission through the sawtooth as we saw through our conventionally polished prism at 157 nm. There is no doubt that part of the RICH detector will be made from sawtooth radiators, as we can eliminate the tilted radiators and obtain much better particle identifcation especially at small values of $\cos(\theta)$. Some final remarks:

- The 15% transmission variations from tooth to tooth, and even within some teeth, were not surprising given that OPTOVAC could not yet use the SX milling machine for cutting the teeth. Nor were the 0.020" radii at the bottoms of the teeth surprising, given that the crystal had to be picked up and rotated half way through the manufacturing procedure (this step was aligned only by eye, and was expected to leave a small region improperly cut and polished at the bottoms). A new tool is being purchased which will reduce these radii to the 0.002" level.

- We hope to use two prisms stacked one on top of the other to measure the absolute transmission of the pair (using 15^o incident angle). Assuming both prisms

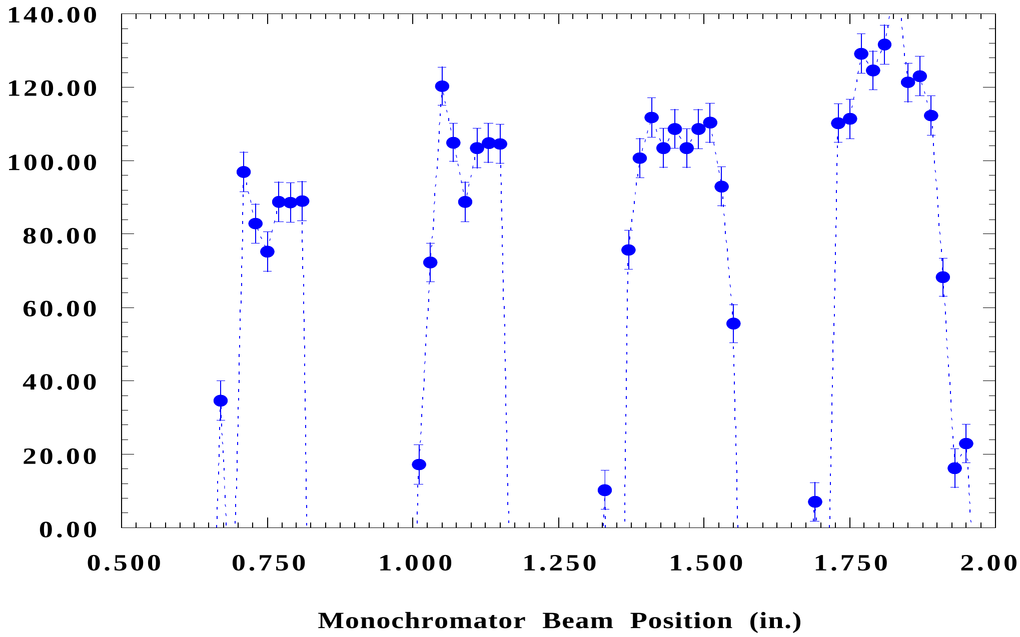

Figure 10: Scan of the light output through the prototype sawtooth radiator with $\theta = -15^o$ and $\lambda = 140$ nm, normalized to the light output through 1 cm of the 45^o LiF reference prism. If we had an ideal sawtooth, each tooth would be a miniature duplicate of the curve in Figure 5.

to be identical, we will then have an absolute measure of the transmission of a prism, to which we then normalize these sawtooth measurements. An absolute measurement is important because a poor quality reference prism artificially exaggerates the apparent transparency of the sawtooth.

- We hope to continue investigating the 3% background observed on the sawteeth and not observed in the prism. Even with the 42^o tooth angle, we expect total internal reflection for the tests described above when the beam is not leaned toward the tooth inclinations. Is the 3% background an irreducible feature of multiple reflections? Would we expect it to go away once the flat surface is coated with the dielectric, as it will be in CLEO? Is there a way to tell where this light is going?

References

[1] A. Efimov et al., NIM A 365, 285 (1995).

[2] S. Kopp, forthcoming RICH note describing the monochromator measurements.

A Overview of the Monochrometer

A.1 Monochromator Apparatus

The measurements that we performed were all done using a VUV monochromator and vacuum tank that we have developed at Syracuse University. The monochromator consists of a deuterium lamp and a diffraction grating to select individual wavelengths. The lamp has a continuous spectrum output in our wavelength band, but a prominent peak at 156.8 nm. The monochromator is mated to a vacuum tank in which the crystals sit on moving X-Y linear stages that scan them through beam. On the other side of the vacuum tank is a glass window and a photomultiplier tube to detect the light. A sodium salicylate coating is applied to the vacuum side of the glass window to act as a wavelength shifter for the UV light.

For these measurements, the vacuum chamber is set up as in Figure 11. The monochromator light beam (A) enters through the bottom of the vacuum tank. The light passes through a 0.020" collimating slit (B). The light may bounce off of a rotateable mirror (C) to produce the 15^o deflection of the beam. At position (D) we place either a crystal or a second collimating slit, depending upon the measurement to be performed (see below). The slit or crystal is mounted upon a moving tray (E) which is carted around by the X-Y stages. The light is wavelength-shifted by a sodium-salicylate covered glass window (F), and then detected in our photomultiplier tube (G). The lower linear stage (X stage) is labelled (H) and the upper (Y) stage is labelled (K). The vacuum wall is labelled (J). In this view, we are looking down the Y axis, and the interior of the vacuum box is 8" tall. Typically, the vacuum used was 1 mTorr. I note that in practice the moving tray (E) was big enough that both the "moving slit" and the two crystals (prism and sawtooth) could be mounted simultaneously and all the measurements performed in one pump- down sequence of the vacuum tank. Also, the mirror (C) was manipulated by a vacuum motion feed-through, so that the angle could be changed for different measurements (as in Figure 11) or the mirror pulled away from the beam altogether (as in Figure 12) during one pump-down cycle.

The systematic uncertainties in the transmission measurements are reduced through a couple of techniques. Before the light beam enters the vacuum tank, it is passed through a shutter which opens and closes at 40 Hz. The resulting square wave of phototube current has an amplitude which provides a measure of the light output which subtracts dark current offsets, etc. Also, in general, a transmission measurement is performed by performing "crystal-in/crystal-out" measurements: we divide the light output when the beam passes through a crystal (as registered by the current in the phototube) by the light output when the crystal is removed from the beam. Measuring this ratio removes drifts in the lamp output or gain variations in the tube over time. The photocurrent signal is stable to $\pm$ 0.5% over 20 minute intervals, and $\pm 1.0\%$ over 40 minute intervals. Individual transmission measurements have a "statistical" uncertainty of typically $\pm 0.5 - 1.0\%$ due to averaging the photocurrent, and a $\pm 1.0\%$ "systematic" uncertainty due to signal drift.

The phototube signal is amplified and read out by an ADC card in a Macintosh PC running LabView. The motors on the X-Y stages are controlled by a commercially-available driver unit which accepts instructions from the PC. The LabView program fully automates the measurements.

Figure 11: Diagram of the vacuum monochromator tank when doing a beam scan of the deflected beam. (A) = monochromator light beam; (B) = collimating slit; (C) = VUV mirror; (D) = collimating slit; (E) = moving tray mounted on X-Y stages; (F) = sodium salicylate covered glass window; (G) = Photomultiplier tube; (H) = X axis linear stage; (J) = vacuum box's wall; (K) = Y axis linear stage.

Figure 12: Diagram of the vacuum monochromator tank when doing a beam scan of the undeflected beam (mirror withdrawn from beam). (A) = monochromator light beam; (B) = collimating slit; (D) = collimating slit; (E) = moving tray mounted on X-Y stages; (F) = sodium salicylate covered glass window; (G) = Photomultiplier tube; (H) = X axis linear stage; (J) = vacuum box's wall; (K) = Y axis linear stage.

A.2 Systematic Checks of the Beam Profile

We have performed several checks of the light beam profile. First, we demonstrate that our monochromator beam is narrower than the nominal tooth surface (approx. 6 mm). We have measured our beam width by placing a collimator slit (D) on the scanning table of our vacuum tank (see Figure 12). This collimating slit is stepped through the light beam and the photocurrent measured at each position of the scan. The measured beam profile is shown in Figure 14; the width is measured to be $\sigma = 0.015$" (in the plane of the slit located on the moving tray). Note that this width is largely defined by the 0.020" wide collimating slit at $Z = 3.00$" off of the vacuum tank's floor. This beam profile was also checked during some of our subsequent tests, where the smearing of various opaque objects due to the beam width (see, for example, Figure 5 below), such as crystal holders, was found to be consistent with the s measured here.

Second, we demonstrate that we can bend the light beam through the 15^o angle. The light is bent with the mirror (C). The mirror location is at z = 5.97", as indicated in Figure 11. To study the bent beam we again employ the second collimating slit mounted in the moving tray, and this slit is stepped through the beam. The beam is observed not to be at its nominal position, but is instead shifted to the left or right, depending upon the mirror angle (see, for example, Figure 11). This is to be expected for a beam bent off at an angle. Note also that no light is anywhere other than the peak, so the mirror doesn't scatter the light unpredictably. For reference, there is a 800 mV signal in our phototube when this collimation and mirror are in place.

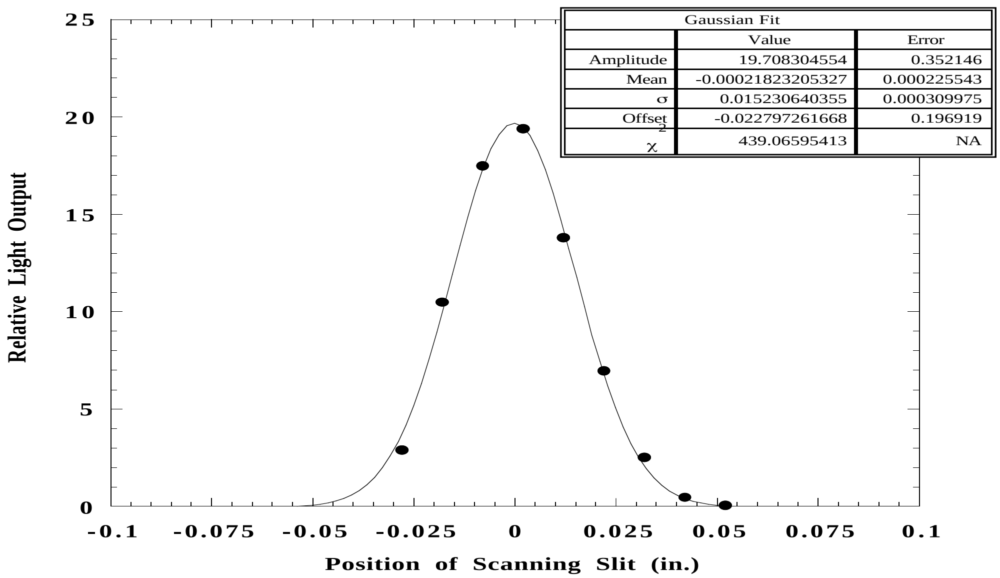

Figure 13: Result of the scan of the collimating slit through the undeflected beam. The resulting light output has a width of 0.015".

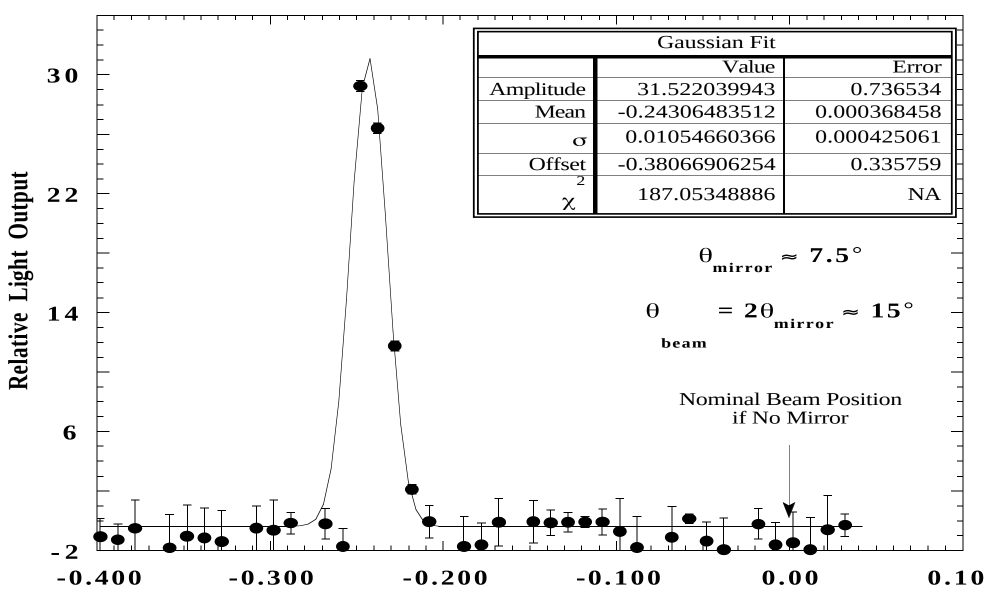

Figure 14: Results of the scan of the collimating slit through the deflected beam. The nominal beam position if no mirror were in place is indicated at 0.00".