3.4 PRELIMINARY DESIGN OF A RING IMAGING CHERENKOV SYSTEM FOR A TEVATRON JET EXPERIMENT

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Imaging Cherenkov detection appears to be the only possible means of identifying leading particles (50-200 GeV/c or more) within jets in a calorimeter-triggered high p_T experiment at 800-1000 GeV onto a fixed target. Segmented threshold Cherenkov counters fail to distinguish any particles beyond 120 GeV/c with helium at atmospheric pressure; partially evacuated counters would be impractically long and mechanically massive. Ionization sampling appears impractical beyond about 70 GeV/c because of the density effect; furthermore, the relevant technique (track projection chamber) is rumored to have fallen into difficulties in attempts to implement it at PEP. Transition radiation appears difficult to use at energies this low when the particles are not deflected away from the TR photon detector. Thus we are led to some Cherenkov imaging scheme, unless some other physical effect has been overlooked. Of the ring-imaging techniques, the near-ultraviolet and visible image intensifier technique of B. Robinson et al., (E-609) is tentatively rejected for reasons elaborated below (cost and optical difficulty), leaving us with the choice of ultraviolet imaging photon detectors. We refer to CERN report CERN-EP/80-115, 27 June 1980, by T. Ypsilantis et al., submitted to the Uppsala LEP Conference, has been the main stimulus to this report, as well as conversations with R. McCarthy (E-605) and P. Kenney of the Notre Dame group.

Most of this report assumes the success of "TMBI" or "TMAE", low-ionization threshold gases currently being experimented with. The reason for this should be apparent from Fig. 1 which shows the oxygen-absorption spectrum. At the TMBI + quartz window passband of 6.47-7.2 eV (2000-1700 Å) the absorption coefficient is < 5 (atm cm)$^{-1}$; 2 (atm cm)$^{-1}$ is a guess at a weighted average so that 5×10^{-5} fraction of oxygen in the radiating gas would give 10% loss of light in 10 meters. This is to be contrasted with the vacuum ultraviolet (~8.5 eV) where the absorption is about 100 times worse, making achievement of the required gas purity almost impossible instead of extremely difficult. Nearly as serious a constraint is the dispersion of radiating gases. Helium is satisfactory in the vacuum UV; but as we will see the required length of radiator is too large and the threshold is actually too high for much of what we want to study. Neon may be useable (but expensive), but only if the photoelectron yield is higher than we assume here. Argon, or argon-helium mixtures with more than a few percent argon, have too high a dispersion in the vacuum ultraviolet for more than a rather poor ring radius resolution. If TMBI etc. work, the dispersion is still the ultimate limit on resolution. We have, after some searching, found a

ABSORPTION CROSS SECTION OF OXYGEN IN THE VACUUM REGION OF THE SPECTRUM

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Received 16 September 1964

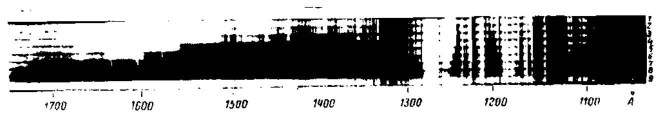

Fig. 1a. Spectrum of the hydrogen lamp. 1 and 9- in the absence of absorption, 2-8- as the pressure of air in the spectrograph is inreased for 0.01 to 1 mm Hg.

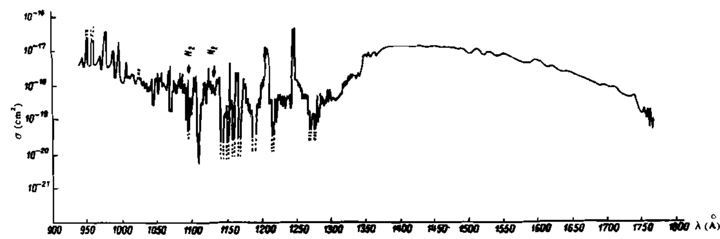

Fig. 1b. Absorption cross section of oxygen.

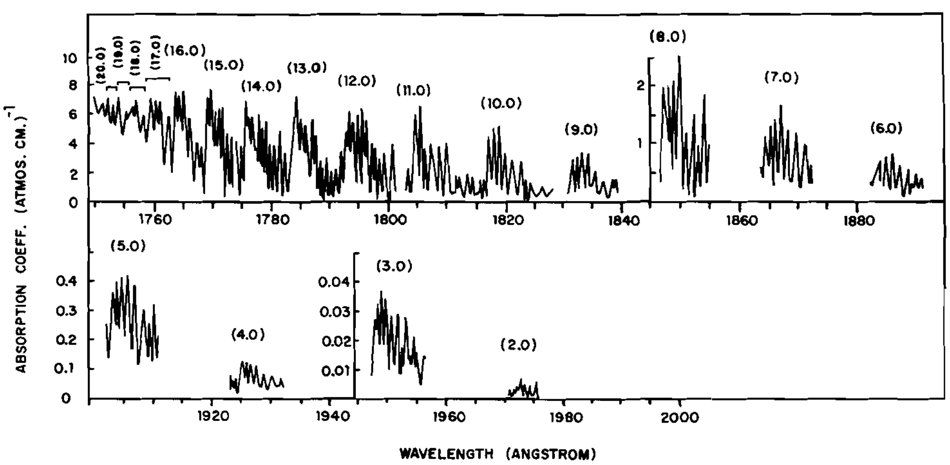

Fig. 1c. Absorption coefficients for the Schumann Runge band system.

dispersion relations formula for argon refractive index; at atmospheric pressure it is

$$n - 1 = 1.2048 \times 10^{6} \times$$

$$\frac{0.209646}{0.87882 \times 10^{10} - \nu^{2}} + \frac{0.209646}{0.91001 \times 10^{10} - \nu^{2}} + \frac{4.941724}{2.6936 \times 10^{10} - \nu^{2}},$$

where ν = wave number in cm^{-1} (Zaidel and Schreider, "Vacuum Ultraviolet Spectroscopy"). This yields $n - 1 = 345.7 \times 10^{-6}$ at 1700 Å, 322.1×10^{-6} at 2000 Å, a change of 7%. (These authors report experimental checks of this formula, interestingly enough using Cherenkov cone angles!) Finally, the least serious objection is the window material; fused quartz would present the least problems but P. Kenney suggests a "stained-glass window" (an expected suggestion from Notre Dame) of smaller CaF_2 segments would be cost-effective and not obstruct much light. Thus, we sincerely hope that lower threshold organic vapors will prove practical, but do not totally reject current vacuum ultraviolet studies.

We have decided to work out the parameters of this report "backward," i.e., assume a detector length (5 meters), a conservative photoelectron efficiency (50 $\sin^2\theta$/cm), a specified number of photoelectrons per ring (6) and then find the required refractive index, thresholds, image size, resolution, etc. The 5 meters is determined by the proposed geometry; we are here considering only identification within high p_T jets into the calorimeter although a separate Cherenkov system using pure helium for the forward particles may be considered in a future report. 50 $\sin^2\theta$/cm photoelectrons is based on the **present** Ypsilantis detector without planned improvements, and some pessimism about the as-yet unmeasured quantum efficiency of TMBI or TMAE. Note however, that the passband in electron volts (the Cherenkov spectrum is flat when plotted vs. eV) is comparable for vacuum UV TEA and for TMBI (Figs. 10 and 13 Ypsilantis report). The 6 photoelectron requirement is an assumption about the pattern recognition needs in a multiparticle situation with overlapping rings; remember that we know the locations of the ring centers so that pattern recognition with isolated particles may only require 2-4 photons. To allow for other assumptions by the reader and future fixing of these parameters (hopefully improvements) we will show how the answers vary with these parameters.

Now

$$\sin^2\theta = 1 - \cos^2\theta = 1 - \frac{1}{n^2\beta^2} = 1 - \frac{1}{n^2}$$

at $\beta = 1$ but at threshold

$$\frac{1}{\gamma_{th}^2} = 1 - \beta_{th}^2 = 1 - \frac{1}{n^2}$$

since $n\beta_{th} = 1$. Thus $\sin^2\theta = 1/\gamma_{th}^2$ for $\beta = 1$ particles.

Furthermore

$$\gamma_{th}^2 = \frac{n^2}{n^2 - 1} = \frac{n^2}{(n + 1)(n - 1)} \approx \frac{1}{2(n - 1)} ,$$

so that if $n - 1$ varies by δ%, γ_{th} varies by ($\delta/2$)%.

Here, with 500 cm radiator, 25,000 $\sin^2\theta = 6$ photoelectrons so $\sin^2\theta = 2.4\times10^{-4}$, $\sin\theta = 1.55\times10^{-2}$ radian and $n - 1 \equiv 1/2 \sin^2\theta = 120\times10^{-6}$ vs 335×10^{-6} for pure argon. Let ρ = fraction of argon and assume $n - 1 = 40\times10^{-6}$ for helium (in ultraviolet; $n - 1 = 35\times10^{-6}$ in visible light) then $120 = \rho \times 335 + (1 - \rho) \times 40$ so $\rho = 0.27$. The dispersion of this mixture is [$\rho\delta$ n(argon)/ n(mixture)] where $\delta = 7$% full width as mentioned above; this yields a full width of 5.4% or a standard deviation $\sigma = \pm1.6$%. This will be a limit on our ring radius resolution.

It appears to us unwise to place the detector in the secondary particle flux, thus we are led to an off-axis configuration as in Fig. 2. The resulting astigmatism is, as we will see, not severe (contrary to my initial assumptions). A 5 meter focal length was chosen to minimize aberrations with mirror sizes defined by the calorimeter; we assume six mirrors each about 1 meter × 1 meter to cover the calorimeter, three above and three below the beam line seen in elevation in Fig. 2. This maximal focal length also minimizes the spatial resolution requirement on the ring radius.

To determine the required detector size, we need the ring size, the out-of-focus target image size and the spread of target size due to target length and p_T kick. The particles go at ~0.07 radius angles, projecting the 45 cm target length to 3.2 cm. At 32 GeV/c (K threshold as we will see) and a p_T kick of ±0.3 GeV/c, magnet center 4.3 m from target, we have a ±4 cm displacement at the target. This is demagnified by 5 m/11.5 m) at the detector or, added linearly, about ±1.4 cm vertically, ±3.1 cm horizontally. The target image is 8.85 m from the mirror or 3.85 m in back of the detector, reducing the 1 m × 1 m mirror size to 3.85/8.85 × 1 m = 0.435 × 0.435 m. The ring size is 1.55×10^{-2} radius × 5 meters = 7.75 cm radius. Thus, horizontal detector

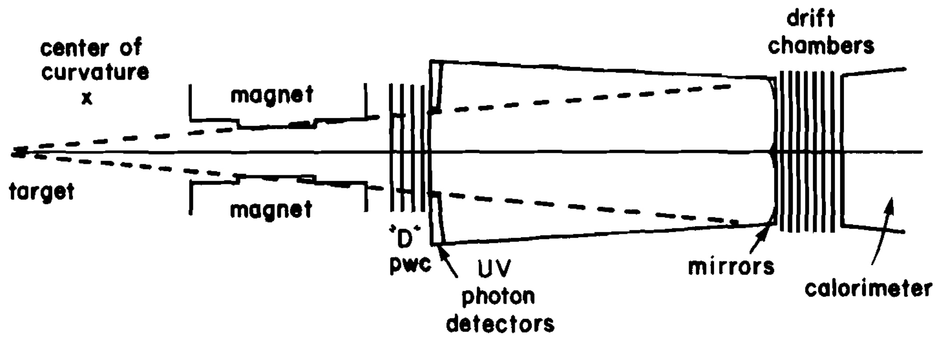

Fig. 2. Possible layout of Tevatron jet experiment, showing 5 meter long imaging Cherenkov counter in elevation view, with the detectors shielded by the magnet.

dimensions should be at least 43.5 cm + 2 × 7.75 cm + 2 × 3.1 cm = 65.2 cm or 26 in., and likewise 61.8 cm = 24.3 in. vertically. Remember that there will be six such detectors, or a total of $2.4 m^2$ area. (Readout will be expensive!)

For the aberrations, we use formulas from Optical Society of America **Handbook of Optics** (McGraw Hill, 1978); we checked the astigmatism formula independently using ($1/f = 2/R \cos\phi$, $(2\cos\phi/R)$ in tangential, sagittal plane where off-axis angle $= \phi$. These formulas are angular diameter of minimum confusion spot $= \beta = 1/128\ g^3$ for spherical aberration, $\beta = [(L_p - R)\theta/16\ R\ g^2]$ for sagittal coma, $\beta = [(L_p - R)^2\theta^2/2\ R^2 g]$ astigmatism where L_p = distance from mirror to aperture stop, R = mirror radius, θ = angle of light relative to radius vector from mirror where it reflects on the average, and g = f number = focal length/aperature. Here we set the aperture stop at the mirror for convenience (since parallel rays are incident for a small segment of the ring) so that $L_p = 0$. The aperture size is the width of the parallel bundle or 1.55×10^{-2} radius times the 5 meter radiator length, i.e., 7.75 cm. Note that it is **not** the whole mirror size; this enters into the calculation of the overall **distortion**, which can presumably be removed in data analysis, but not in the ring blurring which will limit our resolution. Then g = 1/cone angle = 64.5 (again, this is not the f # of the whole mirror, only the illuminated segment) R = 10 meters, and $\theta = 0.070$ radius off axis on the average (by scaling off Fig. 2); we obtain spot size $B = \beta f = 0.005$ mm coma, 10^{-5} mm spherical abberation and 0.2 mm astigmatism. Even for the largest θ the astigmatism is $\lesssim 0.7$ mm, fairly small compared to the dispersion smearing.

What resolution can we then expect? We have $\sigma = 1.6\%$ from dispersion; if we assume 2 mm resolution on photon position (we ought to be able to do much better) 6 measurements of radius give $(2\ \text{mm}/7.75\ \text{cm})/(6)^{1/2} = 1.06\%$ error or vectorially added, 1.9% overall, let's call it 2%. Then, from Fig. 15 in Ypsilantis, 2% or 1 σ difference corresponds to 5 $\gamma_{threshold}$ vs. $\gamma \to \infty$ while 2 σ difference corresponds to 3.5 γ_{th}. Hopefully, we can do better. We tabulate the resulting separation momentum below.

Table 1. Momenta Corresponding To Thresholds, Ring Separation For 27% Argon + Helium.

	γ_{th}	$3.5\ \gamma_{th}$	$5\ \gamma_{th}$
γ value	64.5	226	322
π	4.0 GeV/c	31.5	45
K	32	112	160
p	60.5	211	302.5

For comparison, a 10 GeV/c p_T at 800 GeV energy, 90° cm (43 milliradians) jet of lab momentum 232 GeV/c would yield a leading particle of $z = 0.7$ at laboratory momentum 163 GeV/c, only one standard deviation difference between π and K ring radius. Clearly we'd like to do a little better, although this system is already far superior to threshold counters. How do these parameters scale with hoped-for improvements? Recall

$$\gamma_{th}^2 = \frac{1}{\sin^2 \theta_{max}} \simeq \frac{1}{2(n-1)}, \; n_e \sim 50 \sin^2\theta/\text{cm},$$

so

$$n_e \propto n - 1 \propto \frac{1}{\gamma_{th}^2} .$$

Thus if we could double n_e to 100 $\sin^2\theta$/cm, we could, for the same number of photelectrons (reducing the radiator index) go to $(2)^{1/2}$ times higher momenta. The index would be lowered to 60×10^{-6}, attainable with a neon-helium mixture. The ring diameter, however, would be a factor $(2)^{1/2}$ smaller, perhaps requiring better position resolution. The dispersion would be much reduced even with an argon mixture let alone neon-helium. On the other hand, if more photons are required for pattern recognition, the useful momentum range will be correspondingly lowered.

Finally, we briefly discuss, without derivations, a refocusing system. We assume the target is focused onto a lens (one for each of the six mirrors) at 4 meters from the mirror; this is already close enough that aberrations and distortions are worrisome with a 1 m × 1 m mirror. (The focal length would be 2.97 m.) The resulting image size would be smeared by the Cherenkov cone to about 15 cm diameter required lens diameter. To obtain a 3.1 reduction in image size (the ring images are 1.03 m in front of the lens, only 3 meters from the mirror) requires a lens focal length of 0.23 m and an f number 1.53 (in the ultraviolet-visible range!). The image intensifier (or whatever) would still have to be 8 in. × 8 in. The only way to make it smaller seems to be to further segment the mirror, resulting in a larger number of detectors.

We should conclude with some remarks about readout schemes. R. McCarthy suggests a "visual" readout using amplification to visible discharges and a vidicon readout. This will be slow. The Ypsilantis report suggests a more elegant, but untried, TPC-like scheme. Here, for each of the six detectors, we would have about 320 wires at 2 mm spacing, multiplied by the number of drift regions. If we drift about 10 cm as they suggest, we have

6 regions or 1920 wires; if we scale the drift time at 100 MHZ (0.8 mm drift bins) we will have a maximum drift time of 1.2 μs or 120 counts. It should be possible to do considerable multiplexing of the electronics; it is probably safe to assume only one hit per wire. Nevertheless, this is 11,520 wires, more than the total current MPS PWC system, with a much more complex readout also involving time information. Clearly, some further ingenuity and/or massive effort is called for.