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CHERENKOV IMAGING OF MULTIPARTICLE EVENTS

WITH LARGE SOLID ANGLE ACCEPTANCE

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ABSTRACT

Optical systems have been specifically developed for Imaging Cherenkov Detectors (ICD). They are designed to match vacuum photocathode photodetectors or photoionization detectors which are both in active development.

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1. INTRODUCTION

The Cherenkov effect presents unique and very attractive properties. Particle detectors based on the Cherenkov light emitted by a particle passing through a radiator was recognized as a potentially powerful instrument in 1960 by Hutchinson following an earlier suggestion by O.R. Frisch [1], the called "Cherenkov chambers", as they could give a "pictorial representation of particle trajectory in velocity space".

The basic principles are straightforward and well understood. Practical designs of Cherenkov detectors have been built and many types of successful Cherenkov counters have been utilized in most of the high energy physics experiments. Among all these instruments, those known as "differential counters" (DISC) are not really Cherenkov chambers, they analyze only the particles emitted in a restricted phase space and a limited range of particle velocity β or relativistic factor γ [2]. In fact, they do not produce a pictorial representation of ring images, but only an electronic signature.

There are early exceptions of detectors visualizing the ring images with image intensifiers [3-6]. These attempts did not only prove the feasibility of these detectors but also showed their shortcomings: they are dependent on the performance and availability of image tubes of generally very small useful sensitive surface and they consequently require special optics.

The emphasis on 4π solid angle detection and on multiparticle event analysis near colliders, contrary to fixed target physics where most of the particles are in beams and can be handled with Cherenkov counters, indicates clearly the need for the development of Cherenkov chambers. These are called nowadays RICH or CRID [7-10].

Technological progress in optics and detectors has revived interest in these detectors and is the subject of this report.

New developments of optical systems, efficient in Cherenkov light collection and matched to the size and definition of the photodetectors have indicated possible solutions to the topological problem of the

physical position of the photodetectors. Similar problems are encountered in astronomical telescope designs.

The main collecting element, a mirror, reflects the light against the incoming light and creates obscuration problems when the secondary mirrors or detectors are put in place. Solutions to this problem have also been developed for Cherenkov detectors. Transfer lenses or mirrors of limited size send the focused light outside the detector where the photodetectors are more conveniently installed.

The similarity between these optical instruments stops here. The optical systems differ fundamentally. Whereas the starlight is in plane wave, the Cherenkov light wave associated to a particle is conical and chromatic. The cone angle depends on the wavelength.

The photomultipliers with their high quantum efficiency, around 30%, have been used as photodetectors for many years in telescopes or Cherenkov detectors. Their main drawback is that they are essentially a one-pixel device, costly and bulky.

Attempts at using image tubes and image intensifiers, have been more successful in astronomy than in high energy physics, because they lend themselves to a long integration time useful to measure the sky, but not to the acquisition of interaction events, instantaneous in time and at high repetition rate.

Arrays of photodetectors of similar or better quantum efficiency than the photomultipliers are eagerly awaited by astronomers and physicists.

This paper will describe one of the developments of ICD that has been done at CERN. The problems and relative merits of different optical systems and photodetectors will be discussed.

2. MAIN CHARACTERISTICS OF THE CHERENKOV RADIATION OF INTEREST FOR AN ICD

- (a) The Cherenkov radiation is emitted as a conical wave of light which is attached at its vertex to the particle. The light emission takes

place only above threshold. The γ of the particle must be greater than 10-100 for usual gas radiations. Low energy particles are eliminated. An ICD sees only high γ particles.

- (b) The radiation is proportional to q^2 (q is the charge of the particle) and its intensity has only statistical fluctuations.
- (c) The geometrical definition of the conical wave surface or the Cherenkov photons directions are limited only by multiple scattering and diffraction. To measure the Cherenkov light is the same as measuring the particle itself as far as precision is concerned. Optical systems can be built to achieve the theoretical limit of definition.
- (d) The conical wave is a coherent effect of the light emitted all along a straight track of the particle. The measurement of the wave parameters gives the particle trajectory (angles in space). The usual detectors measure only the average position of a segment of the track, and a fitting procedure is needed to extract the particle trajectory.

The Cherenkov effect with the appropriate optics can considerably simplify the analysis of an event, and even reduce the amount of data needed. A single spherical mirror is by itself an effective optical system for a Cherenkov detector, but its crude performance can be considerably improved.

- (e) Light waves do not interact, therefore particles at very close angular separation produce separately analyzable signals. The double track resolution is limited only by residual optical aberrations and the coarseness of the photodetector matrix.

- (f) The Cherenkov angle θ is

$$\theta^2 \approx 2(n-1) - \frac{1}{\gamma^2}.$$

The measurement of θ is a determination of γ . This determination does not require the knowledge of the magnetic rigidity of the particle.

- (g) All the particles emitted from an interaction with the same γ will have the same signature irrespective of their masses. Correlations in γ are therefore obvious in an ICD and can be obtained without magnetic field analysis or particle identification. This is another way of looking at an event.

The strong points of an ICD are:

- (i) The direct determination of particle directions and angles.
- (ii) The direct determination of γ and consequently the mass and identification of the particle if its momentum is known.

3. DEFINITION OF THE OPTICAL SYSTEM REQUIREMENTS

The performance of the optics is the main limiting factor to the precision of the ICD.

The ICD must adopt a spherical symmetry for a collider geometry. The module of the optics must be stacked without introducing cracks. The equivalent focal length must be adaptable to the detector pixel size.

The optical system must be optically corrected for the range of wavelength usefully detected by the system. The optical system is designed to produce patterns easily analyzable.

Two optically corrected systems have been developed at CERN along these lines. The choice between them depends on the particular size of the interaction region that has to be analyzed.

4. PRINCIPLES OF THE OPTICAL SYSTEMS

4.1 The ring focusing mode

The light is collected by a spherical mirror of radius of curvature R (fig. 1). The ring images are virtual objects inside the radiator. The image of the target region T is at T' . At the position T' all the light for all the particles emitted from T falls symmetrically, where it can be collected by a lens L_1 of radius $= R_{L_1} = \theta \times ST'$. Practically, this

relation indicates a modest size for the lens. This lens can be easily put outside the radiator region by the deflection obtained with a small plane mirror.

The lens L_1 can also be an integral part of the window through which the light goes out of the gas radiator.

The lens L_2 is at a distance e from the lens L_1 . The distance e controls the chromatic correction of the optics and depends on the nature of the gas radiator and the γ of the particles. It can be adjusted at will.

This optical system has been developed and can achieve total geometrical and chromatic correction. Therefore, it produces bright and well delineated images easily and accurately analyzable.

The light is projected as a ring for each particle on a matrix of photodetectors with an equivalent focal length F_E matched to the resolution needed

$$\Delta\theta = \frac{\delta}{F_E} .$$

The pixel size is δ .

This is the ring focusing mode of the ICD. The Cherenkov angle θ is deduced from the ring size. The centre of the ring defines the particle direction without any need to know the vertex position.

The lens system L_1 and L_2 can be seen as a transfer lens, projecting with a magnification or demagnification the ring images at a more convenient place than the focal plane of the mirror which is inside the radiator and traversed by the particles.

The relatively small diameter of L_1 and L_2 contributes to save the dead space around the detector. A real system will contain plane mirrors to direct the Cherenkov light where appropriate. The lenses L_1 and L_2 are doublets or triplets. They are not achromatic.

The converging lens L_1 is equivalent as far as chromatic dispersion is concerned to a negative lens. The lens L_2 is also converging but has a weak positive chromatism.

For a particular value of F_E it reduces to a single lens. The focal length of L_1 is equal to its distance to the main mirror focal plane, therefore this lens projects the ring image at infinity. Moving the lens L_2 and the photodetector array together amounts to changing the distance e and does not change the focusing or the magnification but the chromatic correction of the system. This adjustment can be tuned to compensate for the natural chromatic dispersion of the Cherenkov radiation. When the lenses L_1 and L_2 are in contact, they form an achromatic system and therefore the optical system, mirror L_1 and L_2 , presents no chromatic effect or correction.

The chromatic correction is linear with the separation of the lenses e . Computations show that the lenses can be built with acceptable curvature with elements made of fused silica and the fluorocarbon FC72 [11]. The fused silica will enclose the FC72 which is a liquid.

The combination = fused silica water is not so favourable in general. The cut-off of the optical transmission will be set simultaneously by both substances around 175 nm.

These systems are adjustable to correct completely the chromatism - radial and longitudinal - and are suitable as well for near UV, vacuum photocathodes (mean wavelength $\lambda_2 = 350$ nm, achromatisation wavelength $\lambda_1 = 280$, $\lambda_3 = 440$ nm), as for photoionization detectors with tetrakis (dimethylamine) ethylene (TMAE) ($\lambda_2 = 190$, $\lambda_1 = 180$, $\lambda_3 = 200$).

It is possible with this optical system to stack modules of ICD. If the spherical mirrors are contiguous, there will be no loss of Cherenkov light, but the ring images for particles illuminating more than one mirror will be split between photodetector matrices.

4.2 The spot focusing mode

The lens L_1 can be replaced by a toroid or axicon lens, which will shrink the ring images by a constant amount [12] (fig. 2). The design has been tested and described in ref. [13].

5. COMPARISON OF THE TWO MODES

5.1 Ring focusing mode

- (a) There is no restriction on the length of the interaction region L .
- (b) All the particles produce rings which are sparsely populated with photons. They may overlap and the data analysis is more complicated than for the spot focusing mode. The analysis is probably not fast enough to be used for a first-level trigger.

5.2 Spot focusing mode

- (a) The interaction region must be small for the spot images to be undistorted. The short and small bunches of future colliders are adequate.
- (b) Particles with $\gamma = \gamma_0$ will produce a bright spot easily recognizable on the matrix. A fast trigger can be obtained on these particles.
- (c) All the rings are smaller and much brighter than in the ring mode. The data handling and event analysis is easier and will have less ambiguities.

6. STATUS OF THE ICD DEVELOPMENT

6.1 Optics

The theoretical part of the optics has been developed. The problems associated with the manufacture of the axicon and toroid lenses have been solved and two detectors have been built at CERN [13,14].

For collider applications, large size spherical mirrors of good optical quality are needed. Light mirrors have been developed as a sandwich structure of glass-foam glass-glass welded together.

Mirrors have been produced and tested. In a size of ~ 1 m the thickness of these mirrors will be a few g/cm^2 .

6.2 Photodetectors

The photodetector is the real bottleneck of ICD and the main part of their cost. The data acquisition is obtained from the hit pattern of photons on a matrix of photodetectors.

The quality of the detector is in direct relation with the number of bits of information produced per event.

The occupancy must also not be excessive. If, for example, 20 photoelectrons per ring or spot image are required for unambiguous and precise data analysis, a 1000 particle event will produce $2 \cdot 10^4$ bits.

With an occupancy factor of 10% up to 10^5 to 10^6 pixels are needed.

6.3 Photomultipliers and multianode PM's

The best pixel as far as quantum, efficiency, speed, reliability and availability is the photomultiplier. But at ~ 100 \$ a piece the cost of a matrix built from single PM will be in the range of 10 to 100 M\$, which is unacceptable. Hopefully, industrial progress has been made in multianode PM's - Philips - Hamamatsu TV Galileo-Electro-Optics-(MAMA) [15-16].

A 16-anode array PM from Hamamatsu has been satisfactorily tested at CERN [1/], and 88 anode tubes are in development. Larger tubes seem possible.

To read these multianode tubes a special module is desirable that will interface directly with the matrix of pins of the multianode tube. Such modules are in current development in conjunction with industry at CEN-Saclay.

These vacuum phototubes have inherent advantages:

- (a) They rely on a well matured technology.
- (b) They must be highly reliable.
- (c) They have a sensitivity for the Cherenkov light defined by the relation

$$N_{\text{photoelectron}} = N_o \cdot L \cdot \sin^2 \theta .$$

N_o is the merit factor. For vacuum phototube N_o is 100 to 150 cm^{-1} and reaches in selected tube 180 cm^{-1} .

- (d) They are sensitive in a wavelength interval in the near UV where a choice of glasses and transparent substances of adequate transparency are available to the optics designer.
- (e) They produce extremely narrow pulses, of a few nanoseconds, and can sustain high repetition rate $\sim 10^7$ Hz. They have also their own drawbacks:
 - (i) they must be in general shielded from magnetic fields;
 - (ii) their cost as they are sophisticated items is high, but they are very reliable and need no servicing;
 - (iii) they are not yet catalog items and are available only as prototype or preproduction products.

6.4 Image intensifier tubes

Image intensifiers [6] capable of single photon detection are commercially available (EMI catalog). Their fluorescent screen output must be photographed or video-recorded.

The optical systems previously described are suitable for image intensifier photodetectors. They can produce an image field matched to their photocathode size $\varnothing$ 40 mm, and to their resolution ~ 20 line pairs per millimetre. All these specifications seem perfect for an ICD, but in general it is not possible to gate-on the tube before the Cherenkov light has already reached the photocathode. Therefore, the problem of taking one selected event only among a large number of non-interesting ones rests on the temporary storage of an intermediate fluorescent image.

The control of the fluorescent decay time is limited by the choice of presently available phosphors and is not really satisfactory at high rates.

The image intensifier tube can be used when these effects are taken into account. The number of equivalent pixels is very large $\sim 10^6$ and quite impressive.

6.5 Photoionizations detectors

There are great hopes and a great activity in the field of photoionization detectors. They are quite attractive:

- (a) a large array can be produced in the workshops of high energy physics laboratories;
- (b) the data handling is similar to the one developed at the same laboratories for MWPC or drift chambers;
- (c) they can give the equivalent of a very large number of pixels at a low cost per pixel.

Impressive progress has been made. There are still some weak points. In general the detectors are thick up to a few centimetres. They are volume and not surfacedetectors as is the usual photocathode.

This can lead to serious limits to the precision. The optical images given by optimized optics are as sharp as 50 μm , when they are focused on a plane surface. Even if the photon hit is recorded in three dimensions, with added complexity and cost, the blurring associated to a thick photodetector is not compensated:

- (a) The spectral range of transparency which is compatible with the photoionization range is severely restricted for the available optical substances needed for radiations, windows and lenses. Nevertheless, the new optical system previously described covers the range 180-200 nm, compatible with photodetectors based on TMAE.
- (b) The overall sensitivity to Cherenkov light is so far about one half of the sensitivity of vacuum phototubes [10].
- (c) The vacuum UV range of the useful wavelengths imposes restrictions not only on the choice of optical substances, but also on their purity.

- (d) The data acquisition rate will be more limited than with fast vacuum phototubes. This is in fact a consequence of the much higher number of equivalent pixels. Image intensifiers are even slower, and limited by the picture taking.

7. CONCLUSION

The ICD with vacuum photodetectors is a real possibility with the development of optical systems which can match their size and pixel size. They would be particularly attractive with the new multianode photomultipliers soon to be produced commercially. Nevertheless, if cost is not taken into consideration, they can be built with individual PM's without further R and D, with precisely predictable performances. At very low event acquisition rate, but with high definition, ICD with image intensifiers are also realistic detectors.

Ring imaging detectors based on photoionization are in constant evolution and progress. Detectors based on wirechamber techniques [17], drift chamber techniques [9] and needle counter techniques [18] have been built and successfully tested.

We can consider that Imaging Cherenkov Detectors will soon be in operation near future colliders. The industrial development of imaging phototubes will considerably increase the data rate of acquisition of these detectors and make them even more powerful.

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FIGURE CAPTIONS

Fig. 1 Ring focusing mode optics. Pattern of detected photoelectrons
 on the matrix of photodetectors.

Fig. 2 Spot focusing mode optics. Pattern of detected photoelectrons
 on the matrix of photodetectors.

FIG .1

FIG. 2