The AirWatch Collaboration

AW 9x-xx YYYY xxx
23 October 1998

Use of multi-anode photomultipliers for the AirWatch photon detector

V. Gracco and A. Petrolini
Dipartimento di Fisica dell'Università di Genova and INFN Sezione di Genova,
Via Dodecaneso 33, I-16146 Genova, Italia

Abstract

A preliminary study on the possible use of commercial multi-anode photomultipliers for the AirWatch photon detector is described. It is shown that they fulfil the main requirements. Light collector systems are investigated as a mean to increase the geometrical acceptance of the devices, the low value of which strongly limits the usefulness of the device as it is for the present purpose. It is shown that a large part of the geometrical inefficiency could be recovered by means of a suitable light collector system.

1 Introduction

The choice of the best detector for the observation of the nitrogen fluorescence light induced in the atmosphere by very high energy cosmic rays [1] is a very difficult challenge, due to the many requirements and constraints.

The detector must have single photon sensitivity in the $330 \div 400$ nm wavelength range, which includes emission bands of the nitrogen fluorescence light and where the atmosphere is relatively transparent.

The detector must have a fast response to be able to determine the shower direction from one single observation point and avoid the pile-up of photons produced by very high energy showers.

The detector must have a low noise and good signal to noise ratio to detect the faint signal produced by the less energetic showers and discriminate it from the background.

It must be able to determine the position of the arriving photons as a function of time to be able to follow the space-time development of the shower.

It must have a large area (of the order of one meter), due to the large field of view of the optics, and it must cover the focal surface with a sensitive area as large as possible.

The curved focal surface can be more easily covered by a mosaic of small units.

Only a moderate spatial resolution (of the order of the millimeter) is required.

The large field of view and the spatial granularity require a large number of pixels (of the order of hundreds of thousands) and therefore a sophisticated read-out electronics, capable to handle such a large number of channels, is required.

Low power consumption, low weight, small dimensions, radiation hardness, low sensitivity to magnetic fields, high reliability and operating stability over long periods are the other major requirements.

2 General characteristics of possible detectors

Commercial multi-anode photomultipliers (MAPMT) are now available [3] with characteristics close to the above requirements, in particular concerning the pixel size, the gain, the fast response time and the low weight and dimensions of the device. The most recent devices also show a very low cross-talk and good uniformity in the response, much better than previous ones. Anyway the present devices have a low sensitive to total area ratio, typically less than 0.5. An *R&D* program is under way to find possible solutions to the problem (see below). The small number of channels of commercial devices (≈ 100 channels per devices at most) requires a close packing of a very large number of small devices on the focal surface. If the focal surface is curved the packing of the devices has to be optimized to reduce losses in the geometrical acceptance due to dead regions between the close packed devices. This makes the mechanical assembly more difficult but it would be required to fit a curved focal surface. Care has to be taken in order to protect the photocathode from exposure to strong light, even when the devices are not operated, to avoid damage of the photocathodes and reducing the device lifetime. The response to possible strong thermal variations must also be checked.

We have also considered Hybrid Photon Detectors (HPDs) [2] as possible candidates fulfilling most of the requirements. The use of HPDs for the present purpose would provide a good flexibility in tube design and pixel layout, a stable and linear gain, good spatial uniformity and low power consumption. On the other hand, compared to multi-anode photomultipliers, they require a higher voltage to be operated and provide a smaller signal with the consequent need of a more sophisticated read-out electronics. The actual devices also suffer from a low geometrical acceptance and low number of pixels per device. The dissipation of the heat produced by the electronics chip located inside the tube, the high vacuum required the reliability of the bump bonding and the overall operation stability are additional problems which should be investigated. The use of HPDs in AirWatch would certainly require a long *R&D* (and time) and therefore they probably cannot be considered a viable solution for AirWatch in a short time.

On the other hand multi-anode photomultipliers are a well established technology, available from shelf, with a solid basis in industry and a price which is easily quantified.

3 The R5900-03-M64 Hamamatsu multi-anode photomultiplier tube

Hamamatsu Corporation produces a multi-anode photomultiplier tube (R5900-03-M64 [4]) with 8×8 square pixels of 2 mm side and 2.3 mm pitch, giving a 18.1×18.1 mm^2 maximum sensitive area. The physical dimension of the tube is 25.7×25.7 mm^2. Between any two rows of pixels there is a low efficiency region of about 300 μm width. The ratio between the sensitive area and the total area (geometrical acceptance) is therefore $\simeq 40\%$. The tube is equipped with a bialkali photocathode and a UV-transmitting window. This would ensure good quantum efficiency for wavelengths well below 300 nm, with a peak of 20% at a wavelength of 420 nm.

A possible method to recover the low geometrical acceptance is described below. A new version of the photomultiplier with a 19.5×19.5 mm^2 sensitive area is foreseen by Hamamatsu [5].

The large gain, of the order of $3 \cdot 10^5$ for a 800 V applied voltage, allows to use a simple front-end electronics, without the need for sophisticated fast, low noise and low power preamplifiers.

Assuming to use the Hamamatsu 64-channels tubes about $1.5 \cdot 10^3$ devices would be required to cover the focal surface.

With an applied voltage of about 0.8 kV a conservative estimate of the power consumption is 0.3 W/device and the total power consumption would then be less than 0.5 kW.

The weight of about 30 g per device would give a total weight of about 50 kg.

According to Hamamatsu the anode pulse rise-time is 1.5 ns and the transit time spread 0.3 ns. Cross-talk is 2% and pulse amplitude non uniformity between different anodes is 1 : 5.

Photomultipliers of the same family (Hamamatsu R5900) have recently been used in the AMS [6] detector, designed to be installed on the International Space Station Alpha (ISSA), and whose test flight on the Space Shuttle has been recently carried out with success.

Results of test carried out at recently at Genova and at CERN show a good agreement with the Hamamatsu specifications.

4 Possible solutions to improve the geometrical acceptance

An *R&D* program is under way to find possible solutions to the problem of the small geometrical acceptance, which would otherwise strongly limit the usefulness of the commercial device and appears to be the main limiting factor to the use of the device in our application. The geometrical acceptance could be improved by means of a suitable light collector system, to be placed in front of each device, performing the required demagnification.

This might be either a lens system or a system made of a bundle of tapered light pipes. Only systems of the second kind will be considered in the present note.

The Winston cone [8] has been used since a long time to collect light on photomultiplier tubes. As the Winston cone is a non imaging system it cannot be used on the whole multi-anode photomultiplier. One single tapered light pipe per pixel has to be used, in a multiple Winston cone arrangement. This might exploit either the total internal reflection inside a refractive light guide or reflection on the walls of the pipe (metallic or based on dielectric coatings). Anyway the latter would introduce light attenuation if the number of reflections (with a high incidence angle, on average) is high as is the case. The use of this kind of light collector would have the further advantage of removing dead regions on the focal surface and providing a more uniform efficiency which would help the event reconstruction.

4.1 Tapered light pipes system

The use of tapered light guides to collect light on a smaller detector (or, to diffuse light from a small source) is well known [9]. The maximum achievable demagnification depends on the angular spread of the incoming rays and on the refractive indexes. Squeezing the cross section of a bundle of photons gives rise to a corresponding increase in the angular divergence of the bundle which pose a limit to the total allowed demagnification [8].

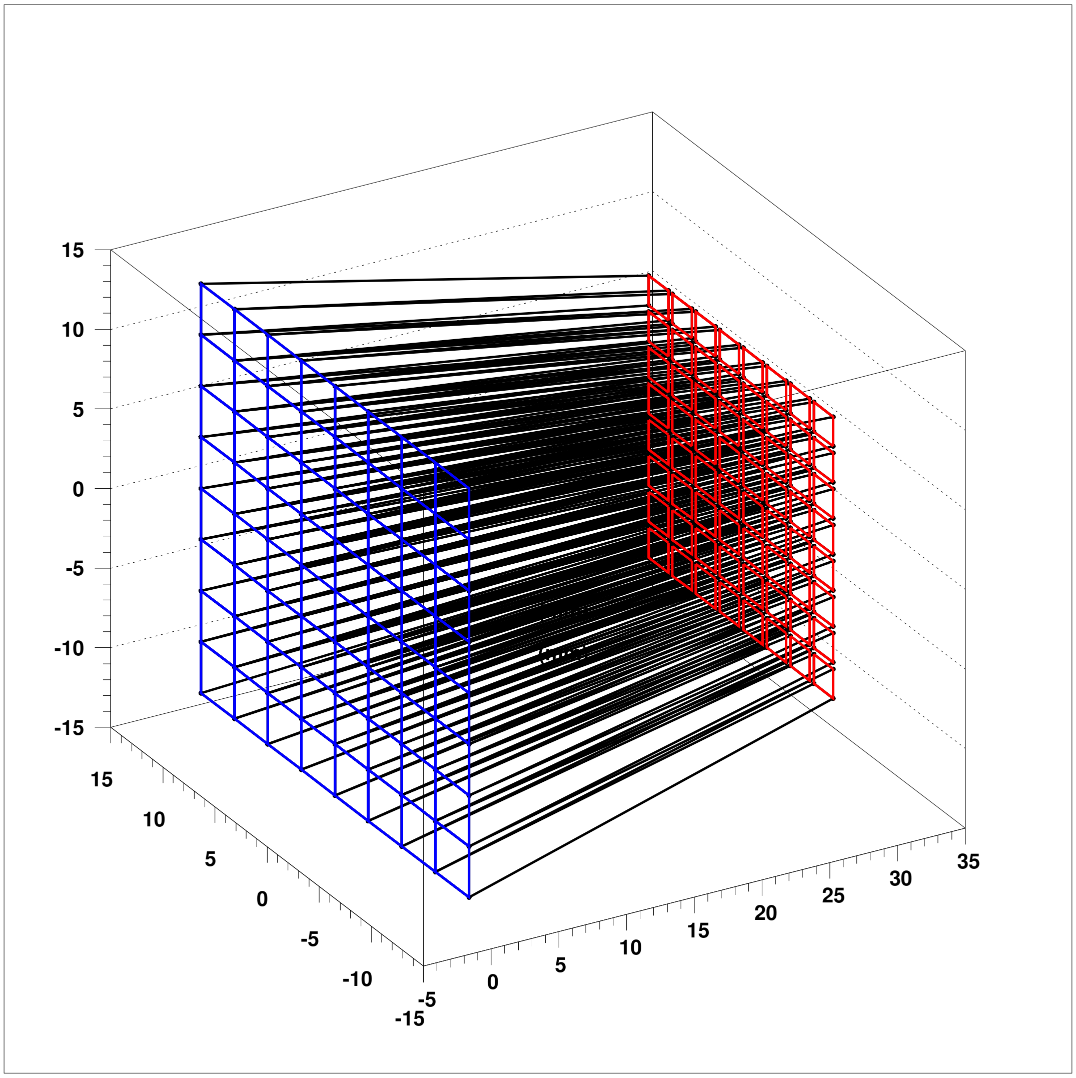

Figure 1: Conceptual drawing of the device: tri-dimensional view (dimensions in millimeters).

One possibility is then to assemble a system made of 8×8 square-section tapered slanted light pipes, one for each pixel, in such a way that the exit face has the dimensions of the multi-anode photomultipliers pixel, and the entrance face has the dimension of $1/8 \times 1/8$ of the 25.7×25.7 mm^2 corresponding to the physical dimensions of the tube. This might even be slightly larger to optimize the packing of the devices on a curved focal surface. The bundle of light pipes should be arranged in such way that a one to one mapping between the 8×8 square pixels in which the physical size of the tube may be ideally divided and the real 8×8 square pixels of the multi-anode photomultiplier is obtained. Each pipe would have the shape of a truncated skew pyramid with square bases. Because of symmetry only ten different shapes are required. Such an arrangement would leave some free space between the pipes, useful to avoid the 300 μm low efficiency region between the multi-anode photomultiplier pixels. This space should be kept at a minimum on the entrance side, to reduce the geometrical inefficiency and may increase to about 300 μm at the exit side. If the system can be assembled leaving this space free the refractive index outside each pipe would be $\simeq 1$. In the case the assembly of the pipes would require to fill this space, then each pipe would have to be coated with a low refractive index material to ensure, as far as possible, total internal reflection. Photons are driven to the photocathode by total internal reflection. The entrance face of the pipes has to coincide with the focal surface. It can be coated with an anti-reflection coating to decrease the reflection losses. The exit face has to be optically coupled to the multi-anode photomultiplier input window. As the material composing the light pipe and the one composing the multi-anode photomultiplier input window would have very similar refractive indexes, the reflection losses at the interface would be small. To minimize reflection losses and avoid total internal reflection on the exit side the light pipe and the multi-anode photomultiplier input window should be in optical contact.

A simplified conceptual drawing of the system is shown in figures 1 and 2.

If the length of the system is too short the rays might reach a point where the total internal reflection condition is violated and the rays will then leak out of the light pipe. In this case not only the photon is lost but, if precautions are not taken, it might show up in another channel. On the other hand if the length of the guide is too long the absorption inside the pipe might become unacceptable. The length of the system is therefore one of the parameters which needs to be optimized. In what follows by "length of the pipes" we mean the distance between the two parallel planes defining the entrance and exit faces of the pipe, that is the two basis of the pyramid, and not the length measured along the axis (which would depend on the geometry of the specific pipe).

The principle of operation is similar (and much less demanding) as the one used in a DIRC [10] detector, where single photons (Cherenkov radiation) are internally reflected $\approx 10^2$ times while being directed to the photon detector inside quartz bars of about one meter long.

4.2 Simulation

The optical performance of the light collector system has been studied by full ray tracing. In the present simulation the exit face of each pipe has been conservatively chosen to be slightly smaller than the nominal pixel dimension (by 0.1 mm) to avoid the possible lower efficiency region at the border of the pixels.

The performance of the system strongly depends on the angular distribution of the incoming rays. In all the cases the position of arrival of the ray on the front face of the light pipe system is chosen randomly and uniformly distributed over the 25.7×25.7 mm^2 of the focal surface region which has to be readout by one multi-anode photomultiplier. Photons are then generated at an average incidence angle with the normal to the entrance face, θ_0, and with a maximum angular spread around the average incidence angle, $\theta_{\max}$. The generated angular distribution is uniform in solid angle. The values used for the different bundles are shown in table 1. In the present simulation the refractive index of the pipe is assumed to be 1.5 while the refractive index outside them is assumed to be one.

The results of the tracing of a few rays are shown in figure 3 for a 30 mm pipe. Figure 4

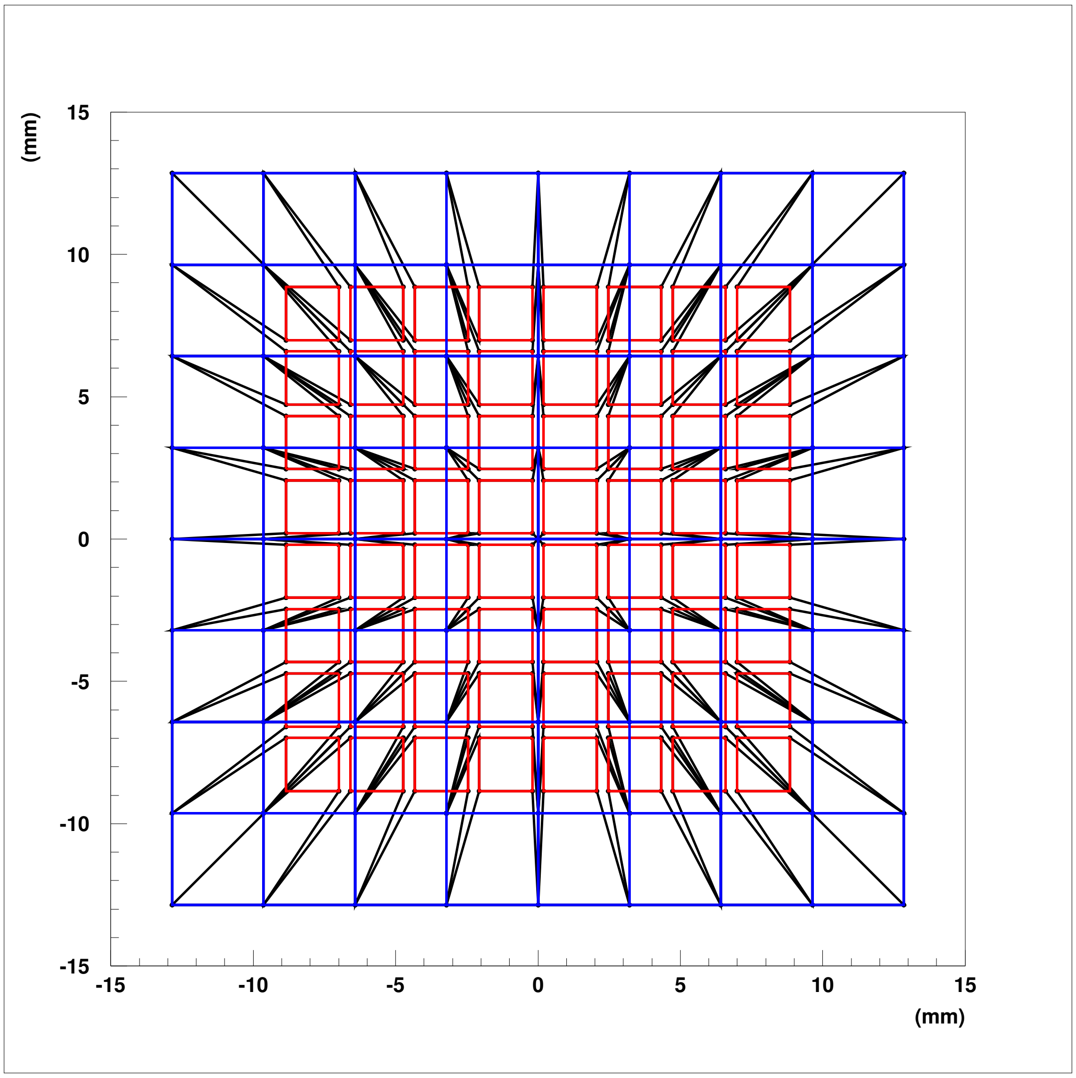

Figure 2: Conceptual drawing of the device: front view (dimensions in millimeters).

shows some rays traced on a 10 mm length pipe, including a few rays leaking out the walls of the pipe. In both figures what appears to be a sudden change in the direction of the ray inside a pipe represents a total internal reflection on one of the walls of the pipe which do not intersect the plane of the figure. In the bottom pipe of the second figure one can distinguish a ray bouncing back.

Results for the different bundles (having different angular distributions) and different lengths of the pipes are shown in figure 5. The number of rays leaking out of the pipe (over a total of 1000 simulated rays per bundle) for different bundles of rays as a function of the length of the pipe is shown. One can see that for a 50 mm pipe, even in the worst condition, that is the case of bundles 4 and 10 which include the highest inclination rays (up to 40° angle of incidence), the loss is below 3%. Anyway if one accepts to lose about 6% of rays the length can be decreased to 30 mm, which would improve considerably the effect of possible absorption losses inside the material. The performance is clearly strongly dependent on the maximum incidence angle of the rays, as can be seen from the figure. If the maximum angle of incidence is kept below 35° a loss of $\approx 3\%$ can be obtained with a 30 mm length light pipe.

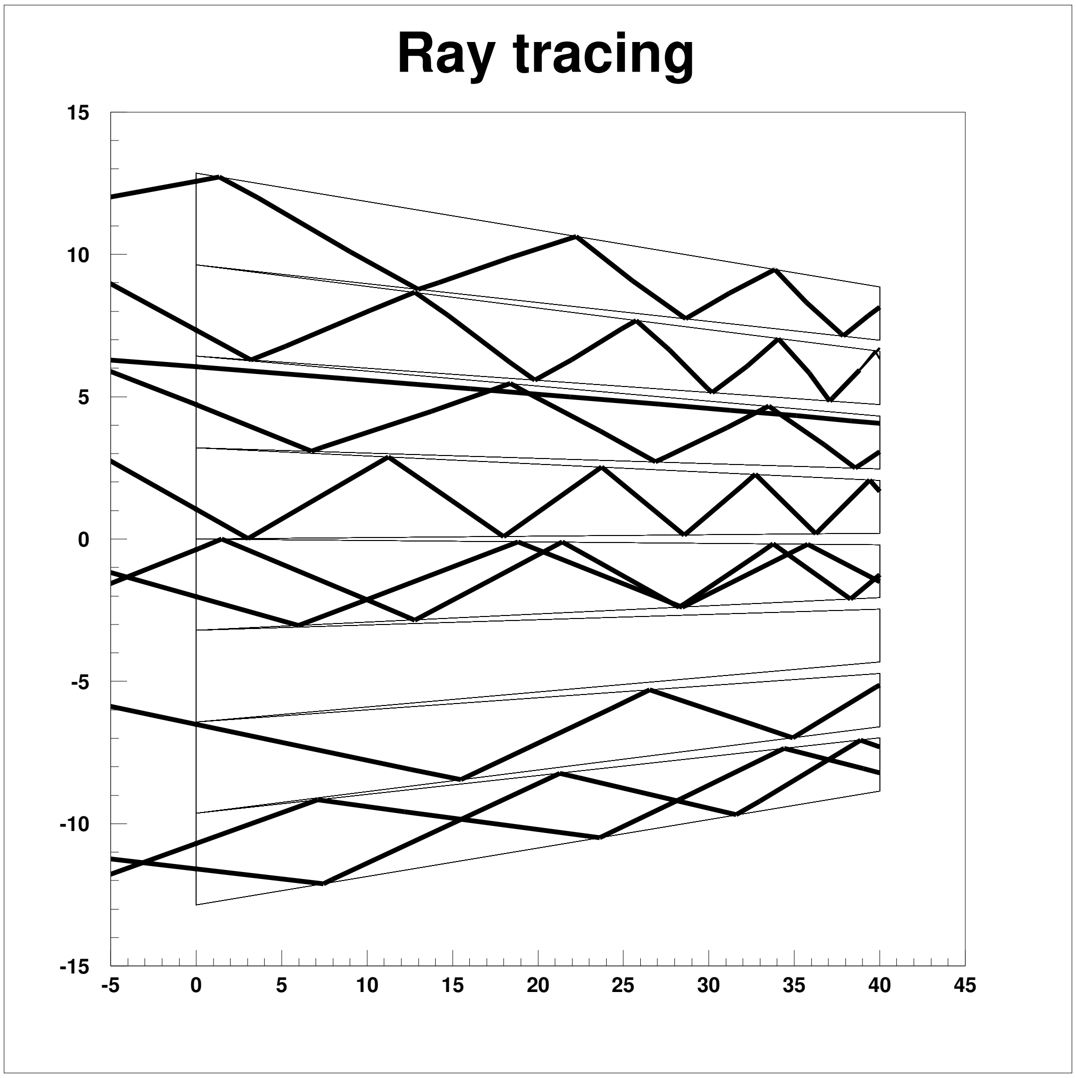

Figure 3: A few rays traced in the 30 mm length pipe system. Dimensions are in millimeters.

The average path length of the photon inside the pipe is shown, as a function of the length of the pipe, in figure 6 for bundle 4. The entries at zero length represent the rays lost due to violation of the total internal reflection condition. This path length is normally only slightly larger than the pipe length because the transverse dimensions of the pipe is normally much smaller than the length and angle between the direction of the pipe and the normal to the entrance face is on average small.

Various angular distributions (incidence angle) for the simulated bundle 10, the most demanding one, are shown in figures 7 (for a 20 mm) pipe and figures 8 (for a 40 mm) pipe.

Figures 9 show the position where the photon is lost. As expected photons are lost mainly near the end of the pipe and mainly in those pipes whose direction differs more from the direction of the incident photons (in the case of the present simulation the pipes with the large y).

The performance of the system has to be more precisely assessed by using the precise angular distribution of the photons for each application.

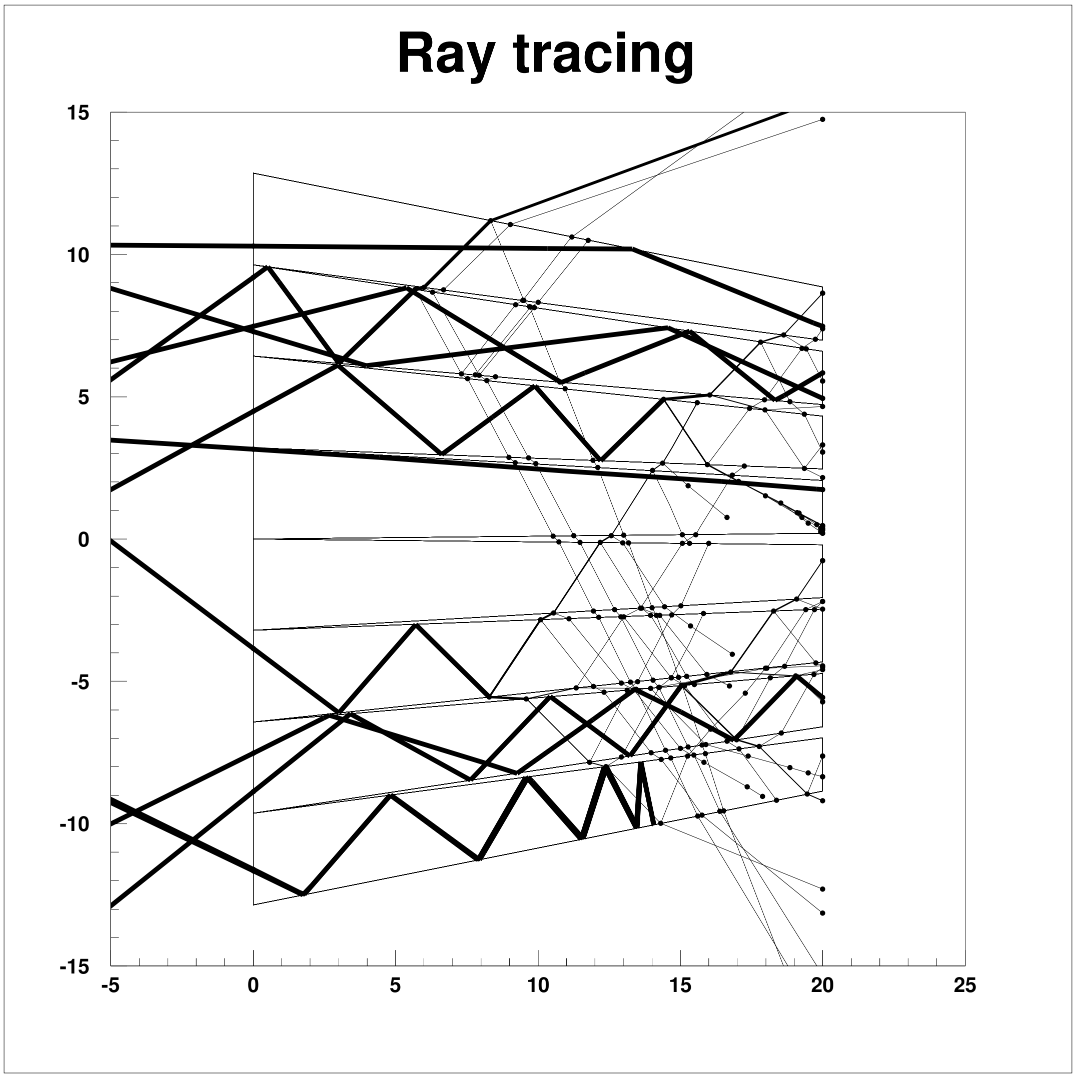

Figure 4: A few rays traced in the 10 mm length pipe system showing a few rays lost along the walls of the pipes. Dimensions are in millimeters.

4.3 Construction of the device

The performance of the system is strongly dependent on the availability of a suitable UV-transmitting material. In fact a successful reconstruction of the events requires that the light losses are kept to the minimum. Quartz would not give any problem for the transmission but would significantly increase the weight. In quartz an average bulk transmission of (98.9 ± 0.2) over 1 m as been measured at 325 nm [10], while the reflectivity was measured (0.9996 ± 0.0001) per bounce [10].

Acrylic with an absorption coefficient lower than $\alpha = 0.1\ \mathrm{cm}^{-1}$ in the wavelength range $320 \div 500$ nm is reported in the literature [7]. Anyway it is well known that the optical properties of acrylic, in particular the transmittance, vary significantly, particularly in the UV region, for acrylic samples from different manufactures and also from different formulations or batches from the same manufacturer. Therefore a detailed study and experimental measurements have to be performed to determine the best supplier and product, both on the raw material and on the final product.

The absorption coefficient and the bulk transmission for 4 cm commercial Acrylic [7] are

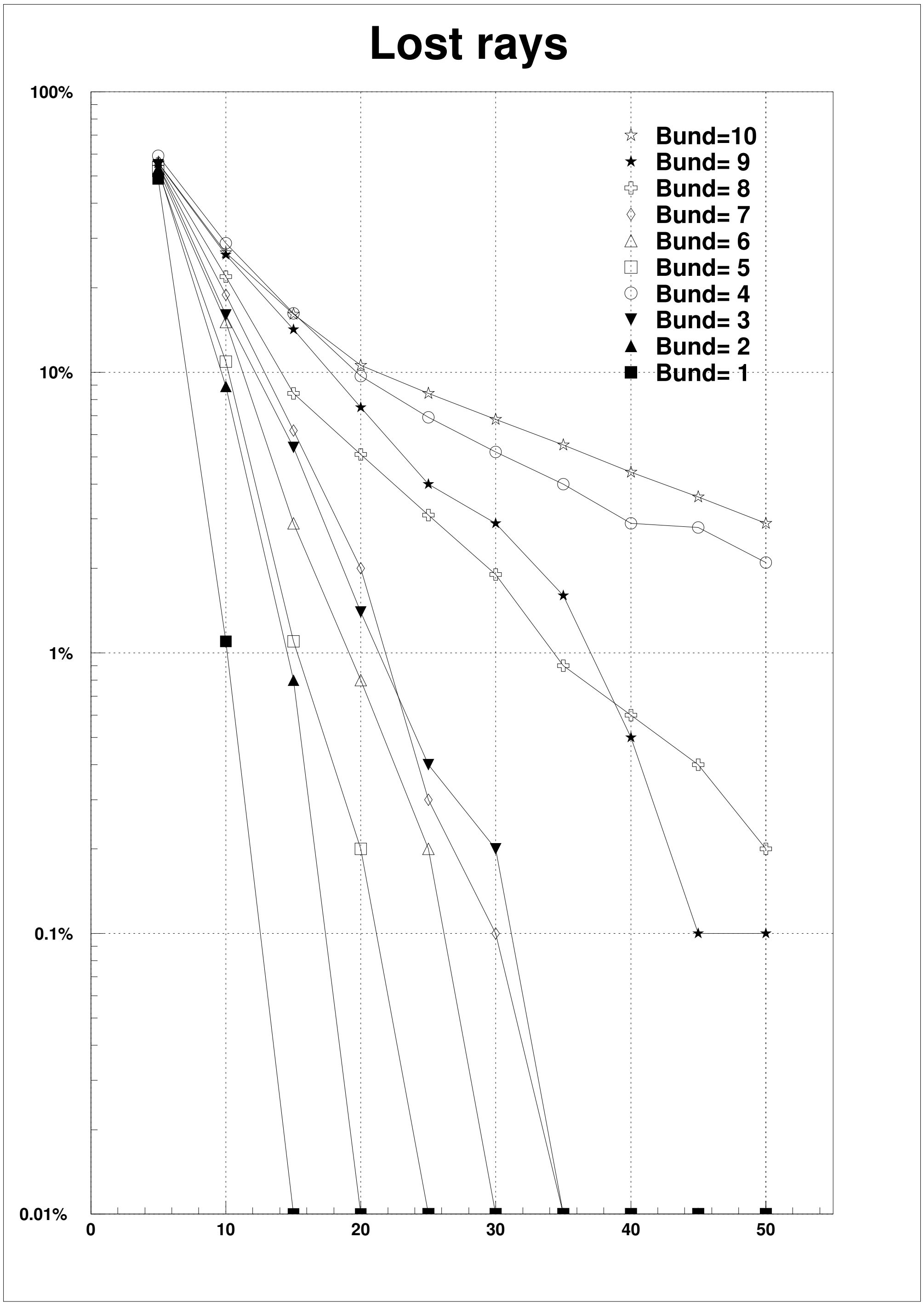

Figure 5: Number of lost rays as a function of the pipe length. The pipe length on the horizontal axis is the distance between the two parallel planes containing the bases of the truncated pyramids.

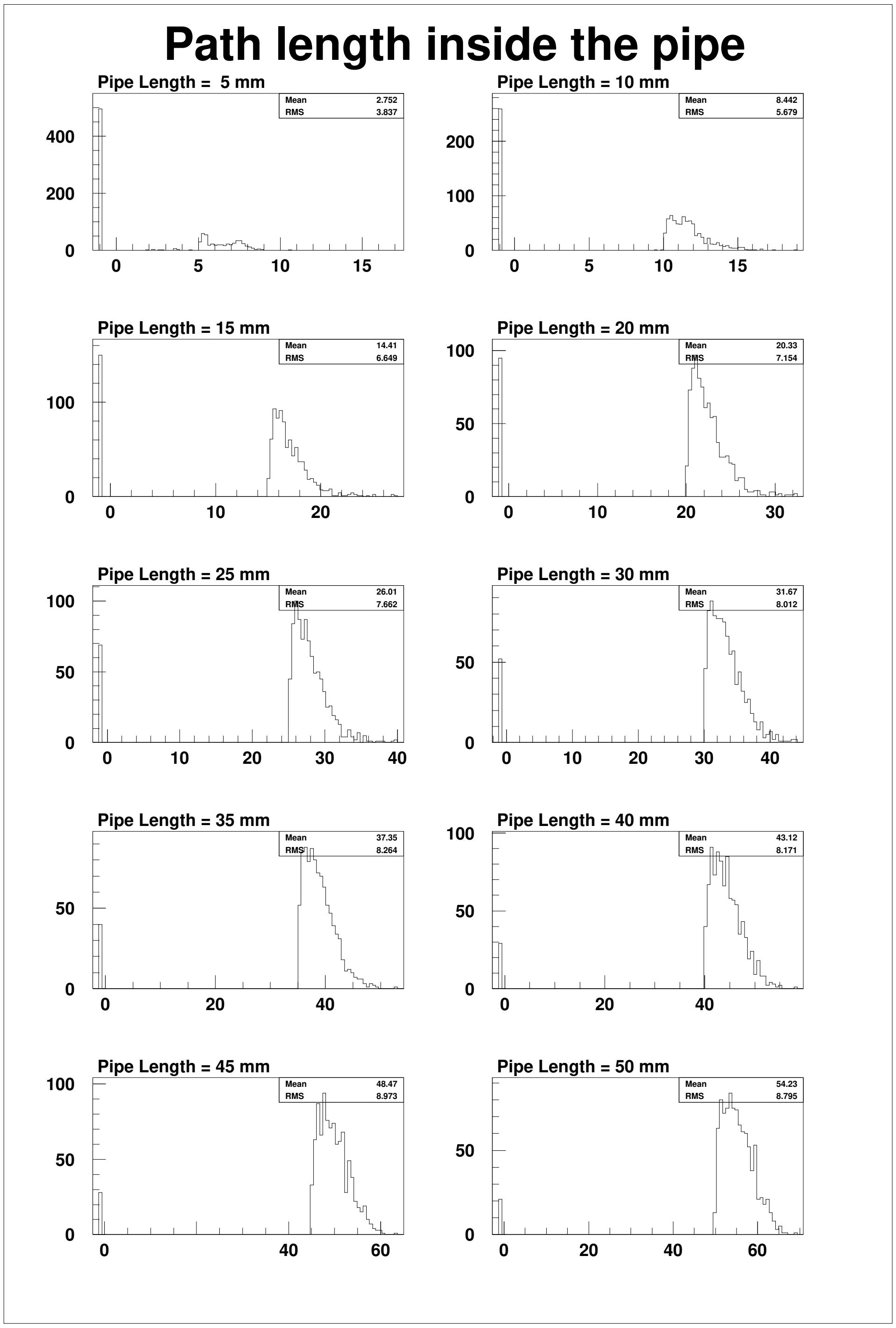

Figure 6: Average path length, bundle 4. The entries at zero length represent the rays lost. Dimensions are in millimeters.

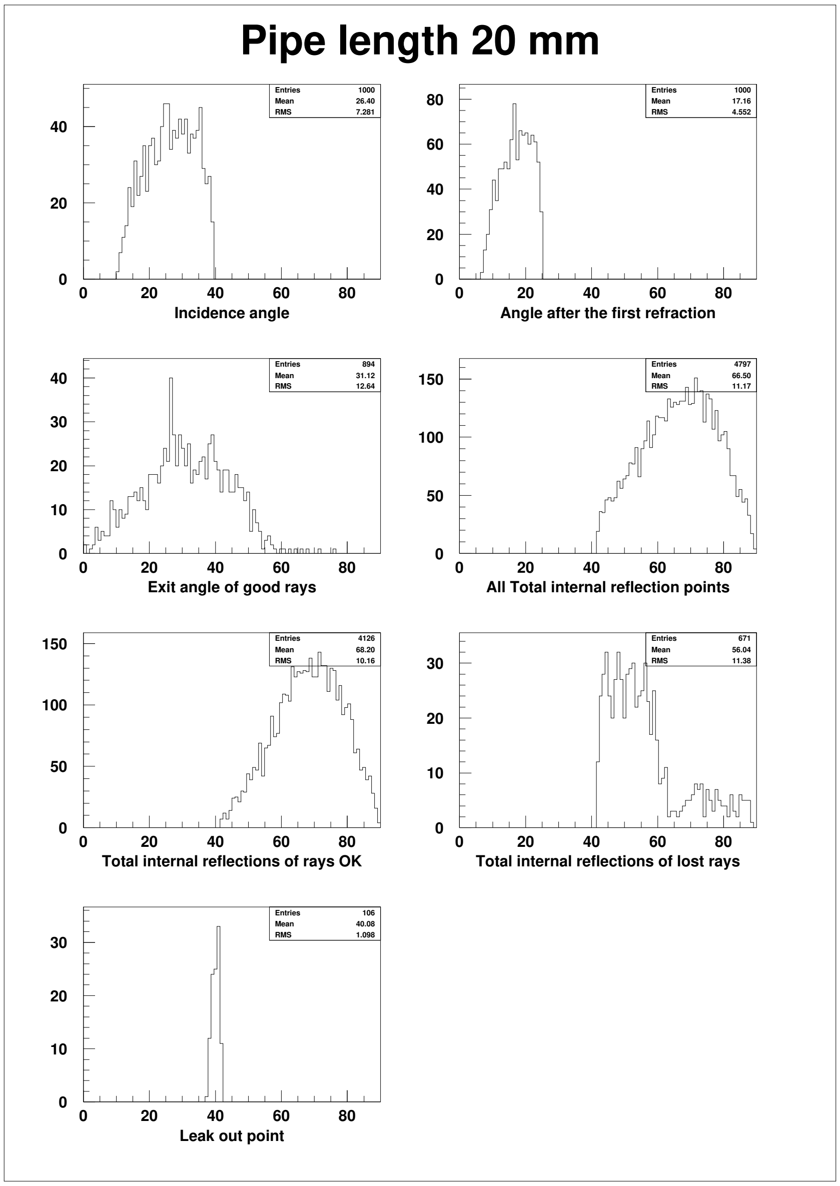

Figure 7: Various angular distributions for a 20 mm pipe and bundle 10. The first plot shows the angular distribution of the rays incident on the light pipes. The second plot shows the angular distribution after the refraction on the entrance face. The third plot shows the angular distribution of the rays reaching the exit face of the pipe. The fourth plot shows the angular distribution of all the total internal reflections. The fifth plot shows the angular distribution of all the total internal reflections of the rays which will reach the end of the pipe. The sixth plot shows the angular distributions of all the total internal reflections of those rays which will leak out the pipe before reaching the exit face (lost rays). The last plot shows the angular distribution of the rays at the refraction where the total internal reflection condition is violated.

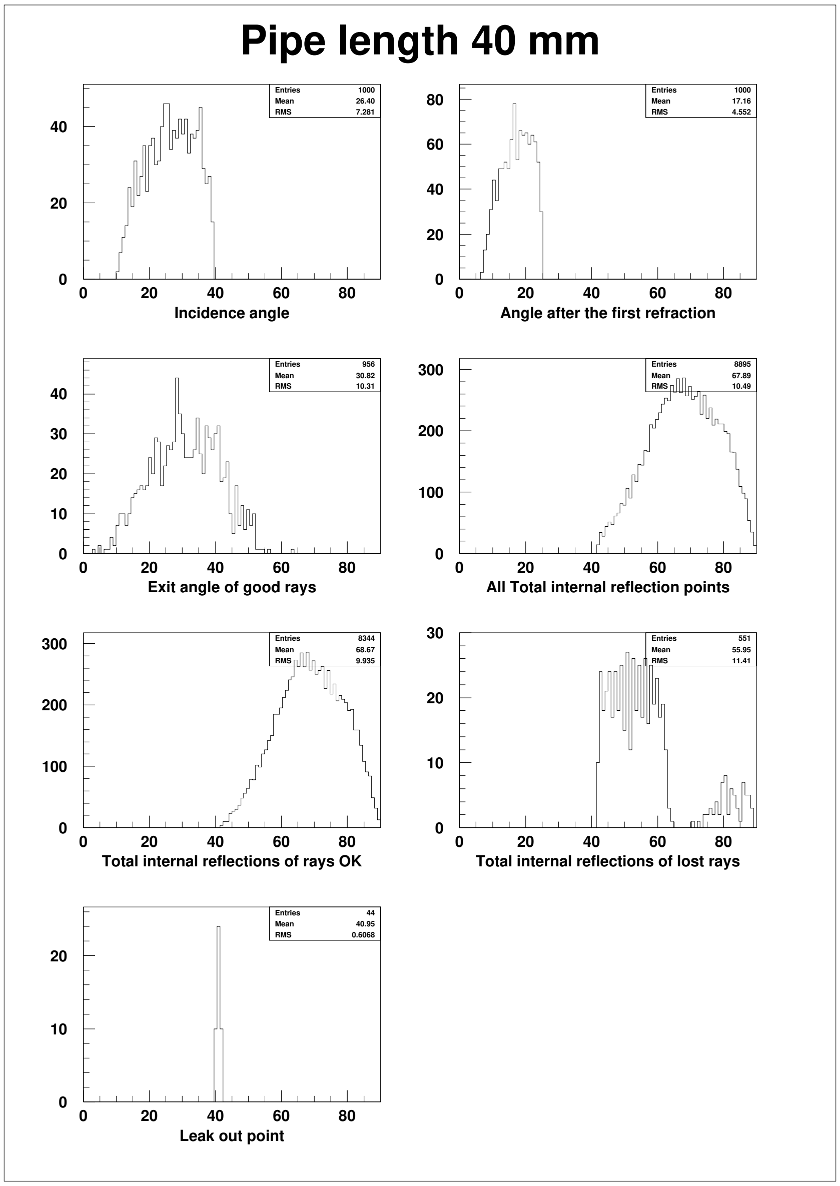

Figure 8: Various angular distributions for a 20 mm pipe and bundle 10. The first plot shows the angular distribution of the rays incident on the light pipes. The second plot shows the angular distribution after the refraction on the entrance face. The third plot shows the angular distribution of the rays reaching the exit face of the pipe. The fourth plot shows the angular distribution of all the total internal reflections. The fifth plot shows the angular distribution of all the total internal reflections of the rays which will reach the end of the pipe. The sixth plot shows the angular distributions of all the total internal reflections of those rays which will leak out the pipe before reaching the exit face (lost rays). The last plot shows the angular distribution of the rays at the refraction where the total internal reflection condition is violated.

shown in figure 10 as a function of the wavelength.

Acrylic is light and can be directly cast with the wanted shape without machining. The cutoff in the transmission at about 300 nm should not affect the AirWatch requirements.

The fluorescence light produced by an atmospheric shower of extreme energy is mainly emitted in the near UV molecular nitrogen lines 337, 357 and 391 nm [1]. Assuming to use a 40 mm length collector from figure 10 one can see that the expected transmission of the light collector in the wavelength range of interest is always better than ≈ 0.85.

Possible methods to build the system are under study. The main requirement is not mechanical precision, because the system is inherently stable for small variations from design values as long as one stays away from the critical conditions where rays start to be lost on the lateral walls because the total internal reflection condition is violated. The main request will be to the smoothness of the walls, to reduce imperfections which would cause ray losses, and in the optical coupling with the multi-anode photomultiplier entrance window.

One possibility would be to assemble the 64 pipes by cementing on the entrance face of the pipes a thin sheet of the some material the pipes are composed of. The exit face might be cemented to the input window of the multi-anode photomultiplier, directly or via a second thin sheet. The sheet on the entrance face would only slightly degrade the performance of the system by making the space resolution slightly worse because the first refraction would take place before the light pipe begins. This kind of device could be made also in quartz, even if it would be quite expensive [11].

Another possible implementation of the device is by means of a fiber optic taper. The main limits of commercial fiber optic tapers are that they are normally made for use in the visible and that the filling factor of the entrance face (sensitive to total area ratio) is normally of the order of 0.75 [12].

Finally the sol-gel silica technology [14, 13], allowing to produce high purity silica optics by means of a molding process, might be used.

The possible integration of the collector system on the tube itself is also being investigated.

The system based on tapered light guides has the advantage that the imaging from the focal surface to the photocathode is not distorted inside the pixel granularity. The inefficient region between pixel and pixel is recovered and no additional surface is added (and reflection losses are therefore not worse than with the multi-anode photomultiplier alone).

In case the system has to operate in an environment with a significant background from high energy charged particles, the impact of the production of Cherenkov light by fast particles passing through the collector, which might be trapped inside the pipe and driven to the photocathode, has to be studied. Anyway in the case of AirWatch a high energy particle

	θ_0	$\theta_{\max}$
Bundle 1	0.0	10°
Bundle 2	0.0	20°
Bundle 3	0.0	30°
Bundle 4	0.0	40°
Bundle 5	15.0	10°
Bundle 6	15.0	15°
Bundle 7	20.0	10°
Bundle 8	20.0	15°
Bundle 9	25.0	10°
Bundle 10	25.0	15°

Table 1:

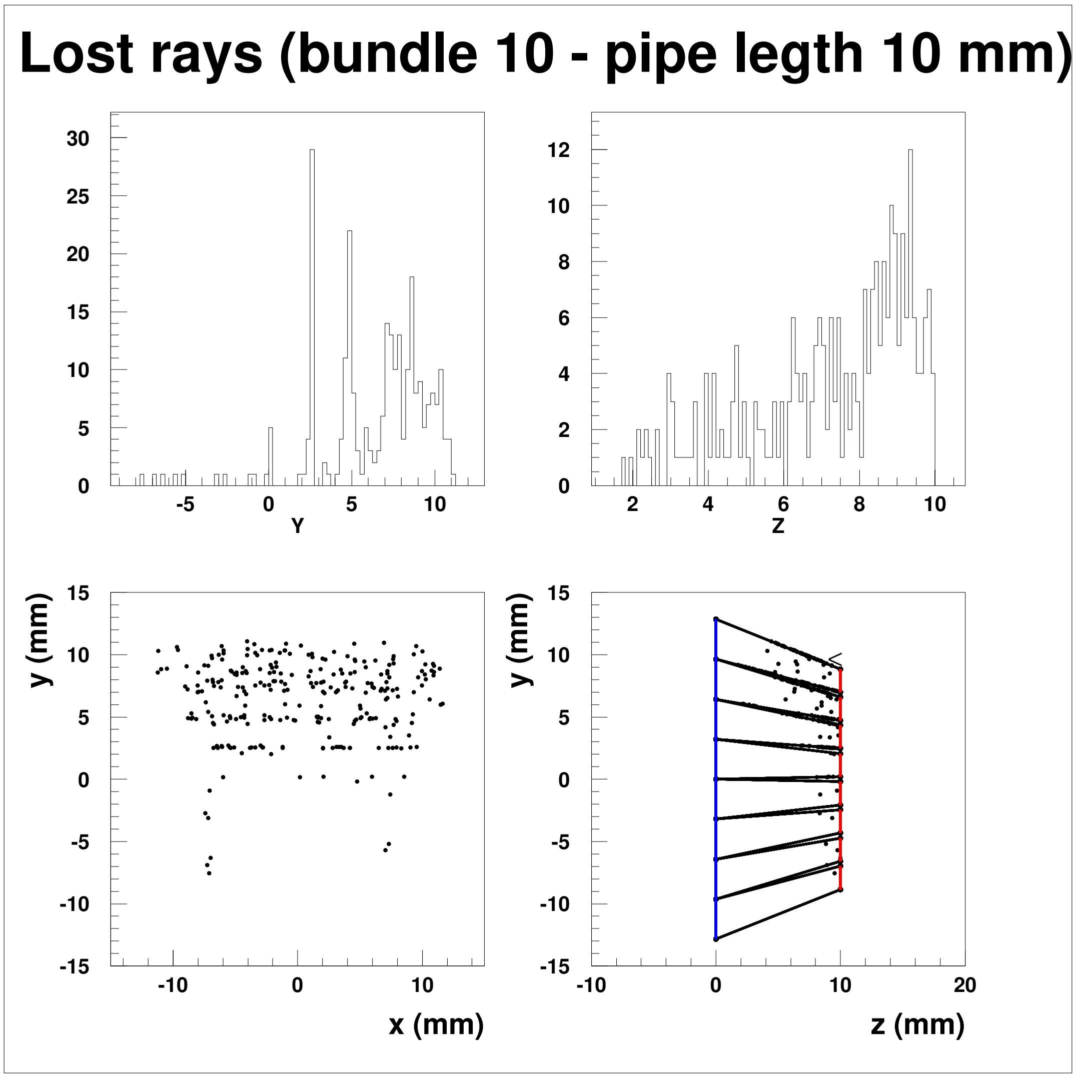

Figure 9: Position where the rays are lost

crossing the light pipes would produce a rectilinear track of varying length (depending on the direction of the particle) but of a very short duration (a few nanoseconds) compared to the much longer signal produced by EAS (of the order of microseconds).

Additional optimizations are under study. For instance the performance of the external light pipes, the most critical as they have to produce the largest change in direction of the bundle of photons, can be improved by giving a suitable tilt to the entrance face.

The use of such a kind of light collector should also be possible in case the focal surface is strongly curved. In this case the entrance side of the collector might be shaped in such a way to approximate the focal surface, giving more flexibility than the use of the multi-anode photomultiplier alone.

The same geometry might be used for a system exploiting reflection on the walls of a set of empty pipes which would have the advantage of no absorption and no limits due to total internal reflection requirement. Anyway the large number of reflection requested and the large range of the angles of incidence of the photons on the wall would require a very high reflectivity in a large range of angles, up to grazing incidence.

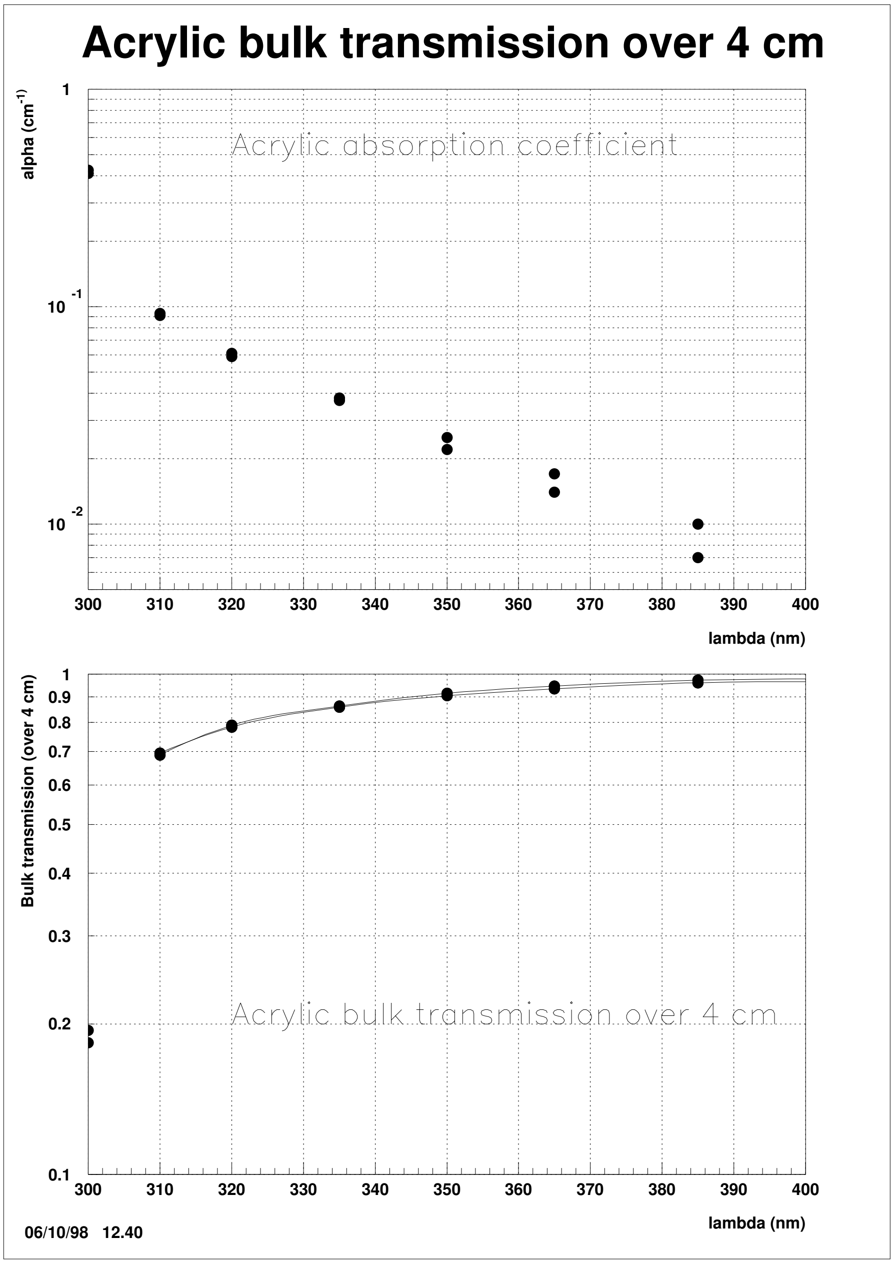

Figure 10: Absorption coefficient and bulk transmission of 4 cm of Acrylic as a function of the wavelength (data from [7]). The two set of points have been recorded using two different methods of measurement.

5 Conclusions

We propose to use commercial multi-anode photomultipliers for the AirWatch detector. Multi-anode photomultipliers are a well established technology, available from shelf, with a solid basis in the industry and they seem to provide a viable solution. They fulfill the requirements of high speed, low noise, low weight and small dimensions. Devices are now available with the required pixel dimension, low cross talk and good channel to channel uniformity. Their high gain allows to use a simple front-end electronics.

The actual price of the device, for large numbers, is of the order of 1.0M£ per device [5].

The main problem with present devices seems to be the low sensitive area. Anyway it has been shown how a large part of the geometrical inefficiency could be recovered by means of a suitable light collection system. Results of a preliminary study of a light collector system to improve the geometrical acceptance of the multi-anode photomultiplier have been reported. The system seems to be able to recover a large part of the geometrical inefficiency producing a rather uniform efficiency on the focal surface. Studies will continue to determine the performance of the system with the real expected angular distribution of incident photons, as the angular distribution of the incident light strongly affects the performance. Anyway the results reported have been produced with what is thought to be a conservative choice of the test rays.

The next step would be to study a possible engineering of the system and carry on a feasibility study of the light collector system. In parallel measurements of the optical properties of candidate Acrylic samples have to be performed to find samples (and suppliers) providing material with the required optical (as well as mechanical) properties. These measurements have to be done both on raw samples and on the machined products as the manufacturing process might affect the optical properties. A full prototype of the collector plus multi-anode photomultiplier system has to be built and its performance to be assessed and compared with the simulation.

The precise geometry of the collector system has then to be optimized according to the shape of the focal surface and the packing of the devices.

References

[1] M. Ambriola et al., Airwatch Collaboration, *Extreme energy cosmic rays (EECR) observation capabilities of an "AirWatch from space" mission*, Nucl. Phys. Proc. Suppl. 70 (1999) 515-517 .

[2] T. Gys et al, Nucl. Instr. and Meth. A355 (1995) 386;
G. Anzivino et al., Nucl. Instr. and Meth. A365 (1995) 76;
R. DeSalvo, Nucl. Instr. and Meth. A387 (1997) 92;
E. Chesi et al., Nucl. Instr. and Meth. A387 (1997) 122.

[3] Hamamatsu Photonics.

[4] Multi-anode photomultiplier tube R5900-03-M64, Hamamatsu Photonics.

[5] Hamamatsu Photonics, private communication.

[6] AMS: Alpha Magnetic Spectrometer, ...

[7] J. C. Zwinkels et al., Appl. Opt., Vol. 29, No. 22 (1990) 3240.

[8] R. Winston, J. Opt. Soc. Am., Vol. 60, No. 2, (1970) 245;
D. A. Harper et al., Appl. Opt., Vol. 15, No. 1 (1976) 53;

R. Winston and W. T. Welford, J. Opt. Soc. Am., Vol. 69, No. 4, (1979) 532;
R. Winston and W. T. Welford, J. Opt. Soc. Am., Vol. 69, No. 4, (1979) 536;
T. Jannson and R. Winston, J. Opt. Soc. Am. A, Vol. 3, No. 1, (1986) 7.

[9] W. J. Smith, *Modern optical engineering*, McGraw-Hill, 1966;
R. W. Ditchburn, *Light*, Academic Press, 1976.

[10] I. Adam et al., (Babar-DIRC Collaboration), *An Internally Reflecting Cherenkov Detector (DIRC): Properties of the Fused Silica Radiators*, SLAC-PUB-7707, Nov. 1997. Poster presented at the 1997 IEEE Nuclear Science Symposium and Medical Imaging Conference, Albuquerque, New Mexico, USA, 9-15 November 1997.

[11] Precision Glass Products Company, Oreland, PA, USA.

[12] Schott Fiber Optics Inc., Southbridge, MA, USA.

[13] Geltech Inc., Orlando, Florida, USA.

[14] Laser Focus World, 12/95.