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# RD46 STATUS REPORT

# High resolution tracking devices based on capillaries filled with liquid scintillator

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## 1. INTRODUCTION

The RD46 Collaboration was formed in 1995 [1] with the aim of collecting competence and expertise in the field of scintillators, scintillating fibre tracking and in the field of photo-detection and optoelectronic technique, in an effort to advance and merge already existing knowledge.

The primary objective of RD46 is the development of high resolution tracking detectors for particle physics, but members of the Collaboration are also investigating interesting applications of the opto-electronic techniques of real-time high-resolution imaging in other fields like astrophysics and medical diagnostics.

The work concentrated in the development of detectors constructed with glass micro-capillaries filled with liquid scintillator [2]. A strong effort was devoted to the development of components, in particular to:

- The study and selection of liquid scintillators (different solvents, different dyes, different purification procedures) with the desired characteristics of emission spectrum, light yield, light attenuation, radiation resistance.

- The development of the technique for drawing and assembling capillary bundles, by collaborating with industry. We have performed quality checks (active volume, array uniformity, mechanical fragility), studied the cutting and filling procedures and measured capillary performance using particle beams.

- The construction of a new system of light intensification and readout based on an Electron-Bombarded-CCD vacuum tube (EBCCD). This new high resolution device for photo-detection has been developed in collaboration with industry and constitutes an area of strong interest for a wide range of applications.

- The study of the new technique of Vacuum Image Pipe-line (VIP) with high time resolution, as a tool for high resolution readout (millions of channels) at high input event rates (40 MHZ) when only a small fraction of events, selected by a trigger, is to be transmitted for further processing.

- The study of a "multiplexing image intensifier" projecting onto the same photosensitive screen, the images coming from different zones of the input window (thus permitting to reduce by more than an order of magnitude the number of output optoelectronic channels for large volume, small occupancy detectors).

In parallel the Collaboration devoted effort in detector design and feasibility studies to investigate the possible application of the developed techniques in different experiments. We mention:
– Study of the potential of the technique for future large scale neutrino experiments that are presently under discussion, like in areas of high resolution tracking/vertex finding or high granularity calorimetry.
– Design of a detector for gamma astronomy (GAMT), based on the high time/space resolution Vacuum Image Pipe-line and the EBCCD readout [3].
– Feasibility study of a Micro Vertex Detector made of thin planar layers of capillaries for beauty decay detection in the LHC-B experiment [4].

In this document we will report on the main results obtained by the Collaboration (since the time of the proposal) connected with the items mentioned in the milestones recommended by the LHCC:

- Production of capillary layers, 1-3 mm thick, $4 \times 20$ cm$^2$. This includes cutting, filling, mechanical quality check, array uniformity, test beam results.
- Test the new capillary bundle with Megapixel EBCCD and the new readout electronics (improved signal/noise)
- Final lab tests of VIP 1 $\mu$s.
- Feasibility study of VIP 20 $\mu$s.

## 2. MEGAPIXEL EBCCD

### 2.1 Development of the Megapixel Electron Bombarded CCD.

The EBCCD, developed in collaboration with Geosphaera, is an electrostatically focused image intensifier vacuum tube with a backside bombarded thinned silicon pixel array CCD in place of the phosphor screen. The specifications of the EBCCD tube [5] that have been achieved are:

- Quantum efficiency ranging from 10 % to 14 %.
- Zoom tube with variable image magnification M = 0.63 – 1.3.
- Fast gating facility.
- Chip with thickness 8 – 10 $\mu$m and light response non uniformity less than 10 %.
- $1024 \times 1024$ pixels. Active area $13.4 \times 13.4$ mm$^2$ (at magnification M=1).
- Gain of about 3600 electrons/photoelectron at 15 KV.
- Spatial resolution 50 lp/mm (at MTF=5 %, M=1).

The low-noise front-end electronics for the EBCCD, developed by INFN-Dubna, performs fast image readout in parallel to the two CCD output registers (10 MHz clock, 100 ns/pixel, 50 ms/full image). At 10 MHz the measured electronics noise level is 110 electrons per pixel.

### 2.2 Construction and test of a full detector based on EBCCD.

A full detector with a large sized capillary target (produced by Schott) has been built, installed in the wide-band muon neutrino beam (near CHORUS experiment) and integrated in the CHORUS trigger and acquisition system. The set-up is shown in Fig. 1: The capillary target is composed of more than $10^6$ capillaries, 30 $\mu$m diameter, 0.9 m long. The readout chain consists of a standard demagnifying image intensifier (a high quantum efficiency first generation tube with a slow phosphor preserving the image long enough for the trigger to arrive) followed by the megapixel EBCCD zoom tube equipped with the fast gating system, the low-noise front-end electronics and a VME frame-grabber designed by the Collaboration. The EBCCD gate is driven by a fast signal coming from a “local” system of scintillating counters which provide a “muon” or a “neutrino interaction” trigger. The CCD readout is started upon confirmation of the CHORUS trigger. EBCCD acquisition is performed with on-line background subtraction and zero suppression.

First results and a comparison with the performance of a similar detector using a "standard" readout (i.e. series of Image Intensifiers and a MCP) coupled to a CCD, have been reported in [6]. The new readout chain is significantly more compact, less expensive and in terms of lifetime, gain stability, single photoelectron sensitivity and spatial resolution it is superior to the standard version. The intrinsic spatial resolution (spot size reported at the input window of the readout chain for the same chain magnification M = 0.7) is $\sigma \simeq 15\ \mu$m, to be compared with $\sigma \simeq 36\ \mu$m obtained with the "standard" readout. In Fig. 2 we report two neutrino interaction events collected, exemplifying the high spatial resolution, the low level of noise and the pattern recognition capability of the technique.

### 2.3 EBCCD as a single photon detector.

At the same time, further tests have been carried out with the EBCCD device as a single photo-electron detector in order to eliminate any preamplifying II stage [7]. Improvements were made in the front-end electronics and in the low voltage supply stability and a Peltier cooler was added reducing CCD dark current and background temperature instability. The total noise level (electronics + CCD dark current) is presently 150 electrons per pixel.

The EBCCD has been uniformly illuminated and images containing of order 10,000 photoelectrons have been recorded and analysed. In Fig. 3 we show the single and double photoelectron peak measured in clusters of adjacent pixels above a given threshold, in Fig. 4 is shown the separation of single photoelectron signal from noise in clusters built around a local maximum.

We consider this an important result and a major milestone of the Collaboration: the capability of single photo-electron detection together with the high resolution imaging performance opens new possibilities in high resolution photo-detection technique and makes this an interesting device for a wide range of, scientific, medical, industrial, applications.

## 3. VIP

### 3.1 Development of the VIP.

The new technique of Vacuum Image Pipe-line has been developed in collaboration with Geosphaera.

The VIP is a high-speed gateable image pipe-line permitting individual images to be delayed and selected from a continuous non-repetitive image stream. The schematic view of the VIP is shown in Fig. 5. The VIP is composed of a vacuum tube equipped with a photocathode at one end, a phosphor screen at the other end, and a system of metal grids in between. Photoelectrons produced by the images focused onto the photocathode, slowly drift forward and backward along the tube, guided by a uniform magnetic field (parallel to the tube axis). By changing the grid potentials, the drift time of the electrons can be varied. Photoelectrons belonging to an image can be selected by an external trigger giving a fast H.V. pulse to the selection grid G1. The selected electrons are accelerated onto the phosphor screen where they reproduce the desired intensified image.

### 3.2 Laboratory tests of the 1 $\mu$s delay VIP prototype.

The tests are finished and results published in Ref. [8]. The measured performances are highly satisfactory: The delay can be tuned from 0.4 to 1.5 $\mu$s, the corresponding time resolution ranging from 4 to 30 ns (Fig. 6). The space resolution was 33 lp/mm with a magnetic field of 0.1 T. To conclude, the VIP can work at an input event rate of 10–100 MHz pipelining more than 50 images, each containing megabytes of information. These performances make the VIP an interesting tool for high-rates H.E.P. experiments or for "fast photography" where high resolution and fast triggerable gating is required, as in the proposed astrophysics experiment of Ref. [3].

### 3.3 Feasibility study of a 20 $\mu$s delay VIP.

First tests indicated an interesting solution using the existing VIP prototype ($\sim 1$ $\mu$s delay): images selected by the first level trigger can be forced (by a fast low voltage pulse applied to the selection grid) to drift forward and backward along the tube for several times. This can be done introducing a negligible dead time. Only the images selected by the second level trigger are finally accelerated toward the phosphor screen and transmitted for further processing. A total delay of 13 $\mu$s with a time resolution of 30 ns was measured (with a reduction of the signal intensity due to the limited grid transparency).

This device could be used in a high rate experiment with a second level trigger delay of 10-20 $\mu$s. In fact this VIP was proposed for the LHC-B experiment, for the read-out of a capillary Micro-Vertex-Detector (MVD). Later on, LHC-B trigger studies demonstrated the need of longer trigger latencies, and the need of the MVD information for the formation of a low level trigger. Under such conditions we consider the use of multipixel HPDs for the readout of the capillary detector a more suitable technique.

## 4. LIQUID SCINTILLATORS

The Collaboration studied many liquid scintillators (LS) obtained with different solvents and newly synthesized dyes, which underwent different purification procedures. One may recall that in the recent past some products have been found to be extremely radiation resistant (order of 100 Mrad) [9]. We selected the best products on the basis of the light yield and light attenuation length as measured in large capillaries (0.5 mm diameter). A light output higher than in good plastic scintillators and further an attenuation length of about 3 m was measured for 20 $\mu$m capillaries. Also, after using the same LS now for 3 years, no significant degradation of the performance was observed (Fig. 7).

Recently the Collaboration investigated the variation of light output of LS in air, in vacuum and in various gases. LS's based on 1-methylnaphthalene or IPN solvent, improve their scintillation efficiency by up to $\sim 30$ % in vacuum or neutral gas atmosphere (Fig. 8), attaining $\sim 63$ % of the light output of anthracene. Temperature dependences of the light output using liquid and frozen scintillators are also under investigation.

## 5. CAPILLARY LAYERS

### 5.1 Development of the capillary technique.

The capillary development was done in collaboration with Schott and Geosphaera. The present capillary technology consistently reproduces good quality capillary bundles (packed arrays of capillaries) with hexagonal or square cross section of up to order of 1 $cm^2$. The manufacturing process starts with the production of single macro-capillaries ($\sim$ 1 mm diameter) of borosilicate glass. Many capillaries are then packed together and drawn at high temperature resulting in a coherent array of microcapillaries fused together in a "multi". Several multies can be assembled together and drawn again to give the final bundle. Starting from similar borosilicate tubes and with different procedures, different array structures can be obtained (see Fig. 9).

An active volume of 80 % has recently been obtained resulting in an average value of $X_0 = 28$ cm for the capillary detector: this is relevant for a tracking device where the maximum information using a minimum of material is welcome.

Uniform planar arrays, suitable for the construction of a large size, low density microvertex detector, can be built assembling small size bundles. The best geometrical bundle uniformity is obtained for multies with hexagonal cross-section. A square cross section is also a good compromise and permits an easier construction of planar structures. Square and hexagonal bundles with and without external cladding with cross section from about 1 to 4 $mm^2$ have been produced by Schott and Geosphaera for test. They have been used for the purpose of gaining the necessary expertise in the technique of assembling, glueing, cutting, filling and building detector prototypes.

### 5.2 Capillary layers

The construction of a planar detector requires assembly of bundles such as to ensure perfect alignment and to minimize the dead space in between. Glueing or re-melting techniques can be used for the assembly. By using a silicon based glue diluted in toluene, we have built several prototypes with an average glue thickness of $50 \pm 14$ $\mu$m. The non uniformity in the glue layer thickness was about 20% translating in a similar relative misalignment of the bundles. We have also demonstrated a reduction in the glue layer to less than 20 $\mu$m. Alternative glues, or combination of glues, will be considered in the future. In conclusion, we are confident to be able to glue bundles with a dead space not exceding 30 $\mu$m (this implies a dead region of 3% for 1 mm thick layers), and with a contribution to the misalignment of less than 10 $\mu$m rms.

We are now studying a second method, which is well known in glass manufacturing, and which consists of producing bundles surrounded by a thin external cladding made of a glass with a lower melting temperature. The layers are assembled and then heated such that the capillary structure is not affected but the claddings are fused and glued together.

The technique for cutting the layers to the specified size and to obtain a good contact with the readout chain input window, has been settled and reproduced several times successfully. A set-up for the capillary filling has been prepared and the procedure has been defined.

The bundle parallelism and the array uniformity of the final layer can be verified by a system illustrated in Fig. 10: the detector is filled with LS and the image of a grid transmitted by the capillaries is observed.

Detector prototypes made of two or three layers have been tested on cosmic rays. The layers are built from square bundles of 14 $\mu$m diameter capillaries and are $30 \times 300 \times 1.8$ $mm^3$. The readout chain uses an EBCCD and is similar to the one illustrated in Fig. 1.

We measured 7.6 hit/mm at 1 cm from the readout and 3 hit/mm at 25 cm. The light yield is high as expected but the light attenuation turned out to be worse than what was previously measured [2]. However the results were obtained with the bundles used to study the prototype building technique which had a poorer glass surface quality. Now that we are capable of handling the technique, we plan to build and test new prototypes with the best bundle quality and best LS to obtain the best measured light attenuation . For detectors 20-30 cm in length equipped with a mirror at the layers far end, we expect to obtain more than $\sim$ 8 hit/mm.

Figure 11 shows the image of a minimum ionizing track recorded by a prototype with two parallel layers. From the figure one can see the enormous potential for pattern recognition offered by this detection technique: large number of hits per unit thickness of material and a good definition of a track vector by a single detector station. We are now developing algorithms for fast identification of ”minivectors” in each layer and to link them together for complete track reconstruction.

## 6. CONCLUSIONS

The RD46 Collaboration had a wide and fruitfull activity developing liquid scintillators, glass capillary technique and various optoelectronic devices.

Referring to the milestones recommended by the LHCC, we have developed and tested the EBCCD readout, the VIP and capillary detector prototypes. At present the results obtained with the EBCCD and the VIP are very satisfactory. In particular, we consider the results on the EBCCD a major achievement of the collaboration. The results on capillary layers are promising but further efforts and tests are needed.

The Collaboration plans to pursue the R&D program at CERN and at the home laboratories, the financial support being ensured by National Agencies, INTAS and a recent grant through the TMR European program.

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[8] "A high speed gateable image pipeline" A.G.Berkovsky et al., Nucl. Inst. and Meth. A380 (1996) 537.

[9] S.V. Golovkin et al., Nucl. Inst. and Meth. A362 (1995) 283.

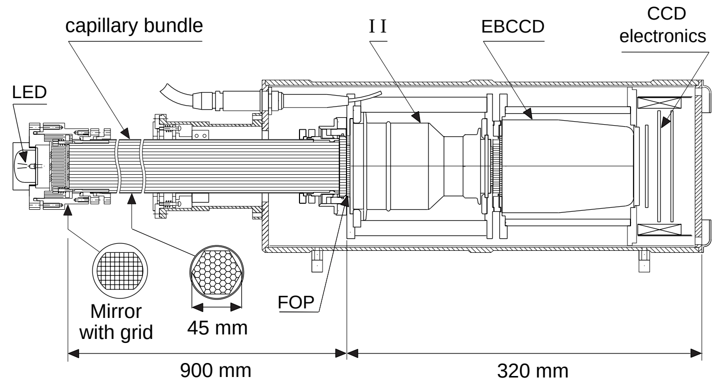

Figure 1: Scheme of the detector with the large-size Schott capillary bundle and the readout chain based on EBCCD. $\sim 10^6$ capillaries read by $10^6$ pixels

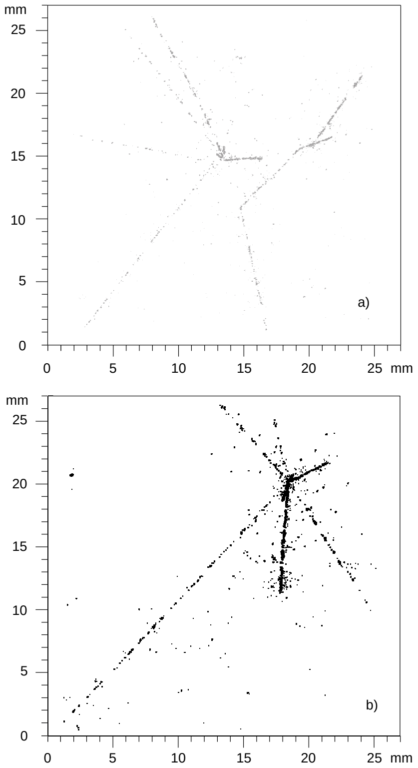

Figure 2: Neutrino interaction events. The beam enters the target parallel to the capillaries. Note the good vertex definition.

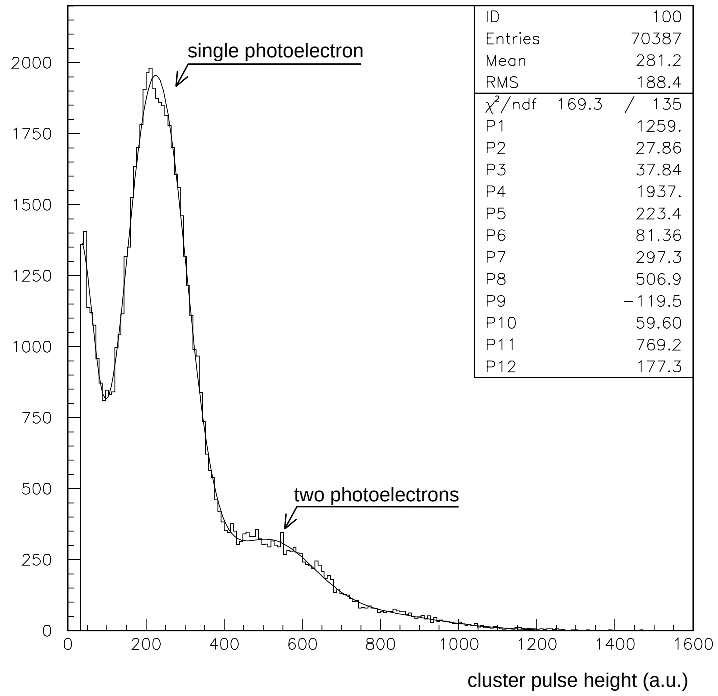

Figure 3: Distribution of the pulse height associated with a cluster of EBCCD pixels above a given threshold. Single and double photoelectron signals are superimposed to a rapidly decreasing background.

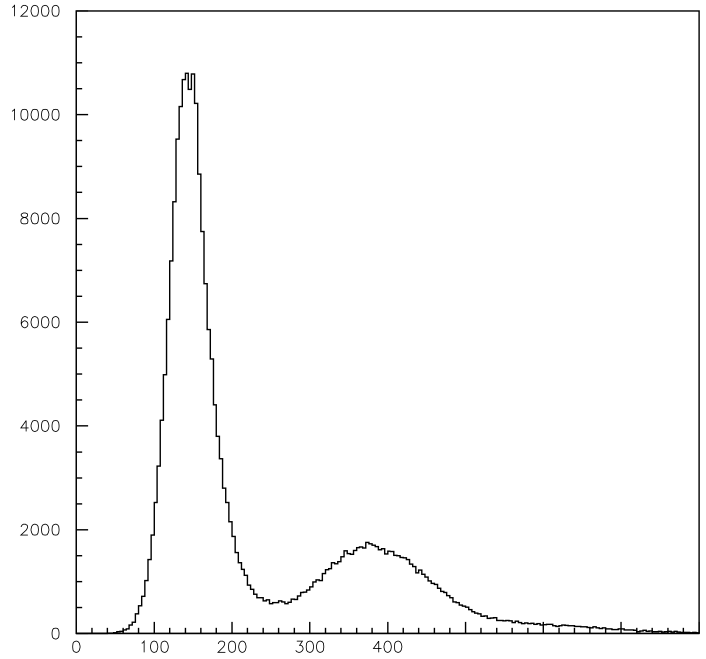

Figure 4: Separation of single photoelectron signal from noise in clusters of 5 pixels, one on each side of a "local maximum". No threshold on pixel pulse height is applied.

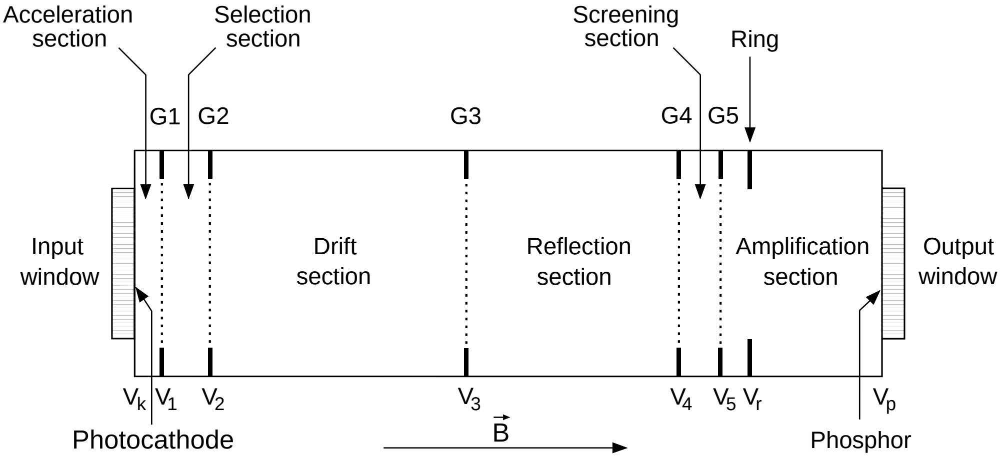

Figure 5: Schematic view of the VIP.

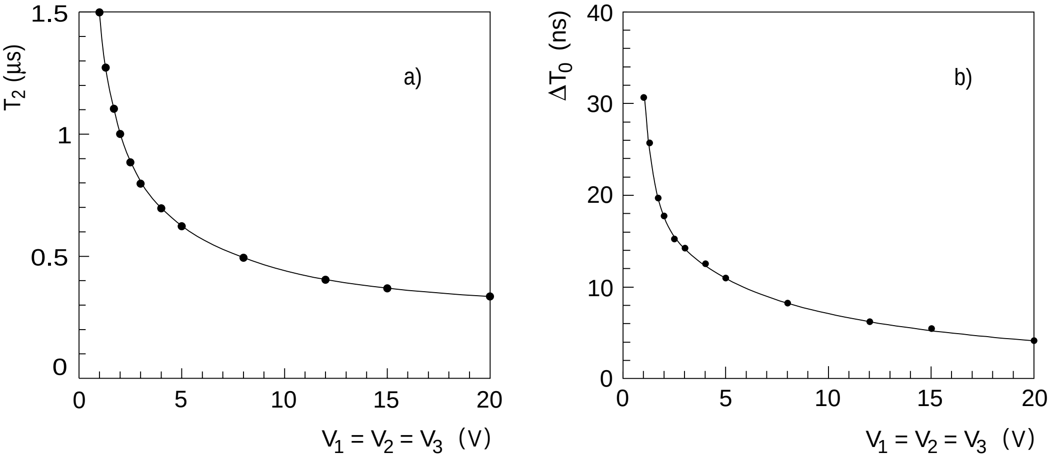

Figure 6: Delay and time resolution of the VIP as a function of the common potential of G1,G2 and G3.

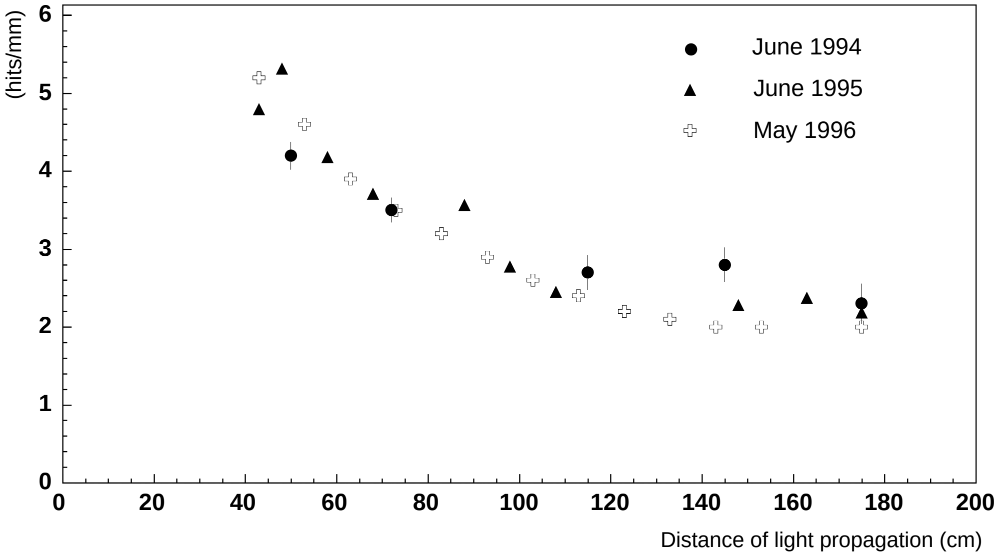

Figure 7: Hit density vs. distance between crossing tracks and readout window.

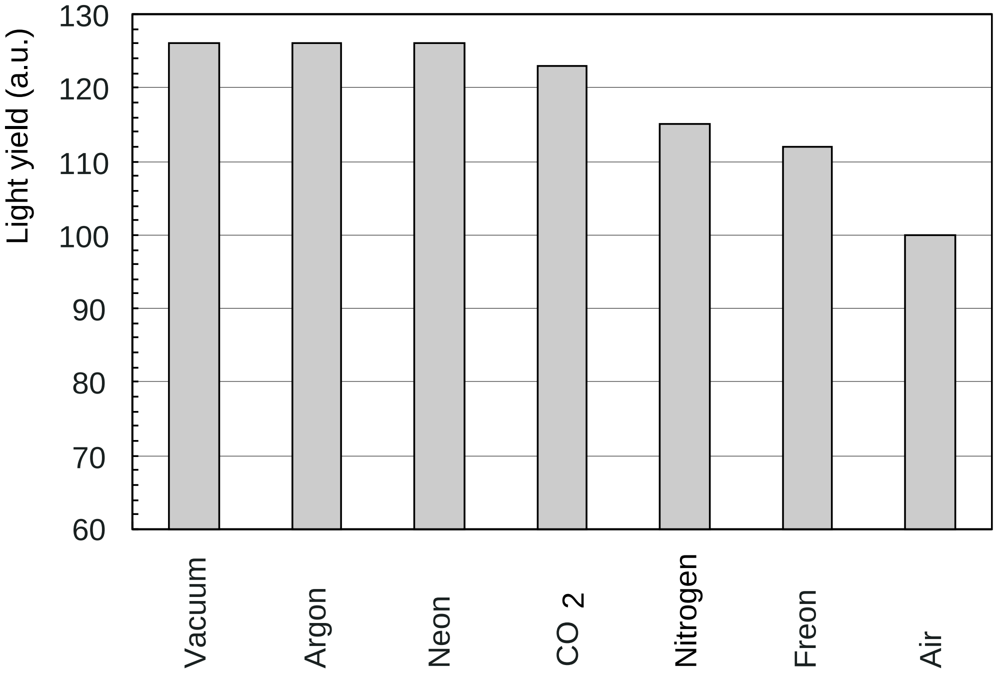

Figure 8: Light output of liquid scintillator exposed to different atmospheres. The value of air has been arbitrarily set to 100.

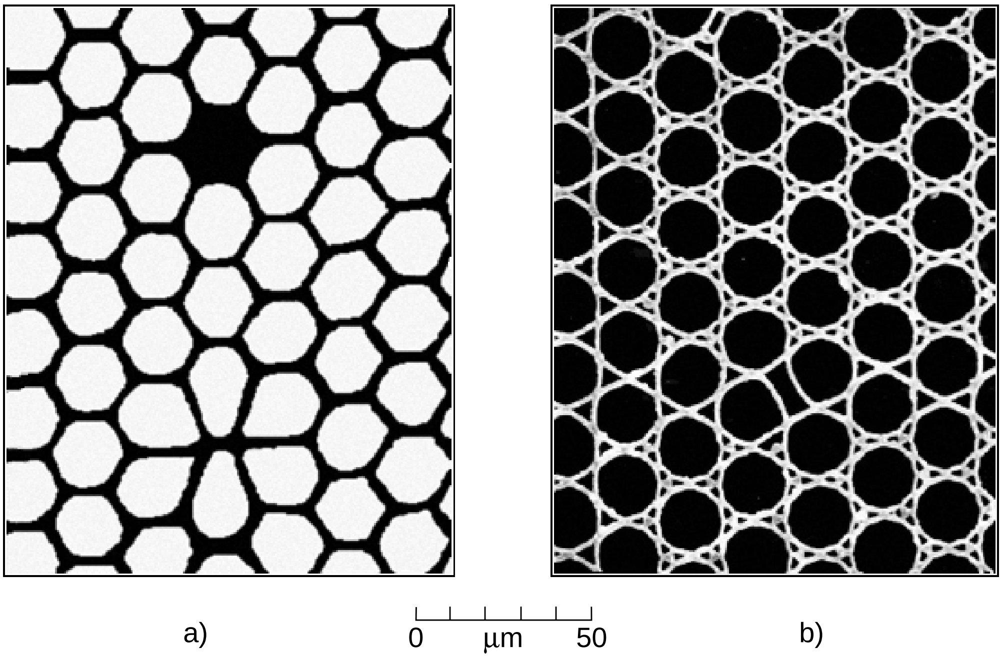

Figure 9: Microscope picture of capillary arrays: a) from Geosphaera; b) from Schott. Areas with defects have been selected. In the array by Geosphaera isolated black fibres act as EMA. In the array by Schott, thin rods of EMA are inserted in the interstices between capillaries.

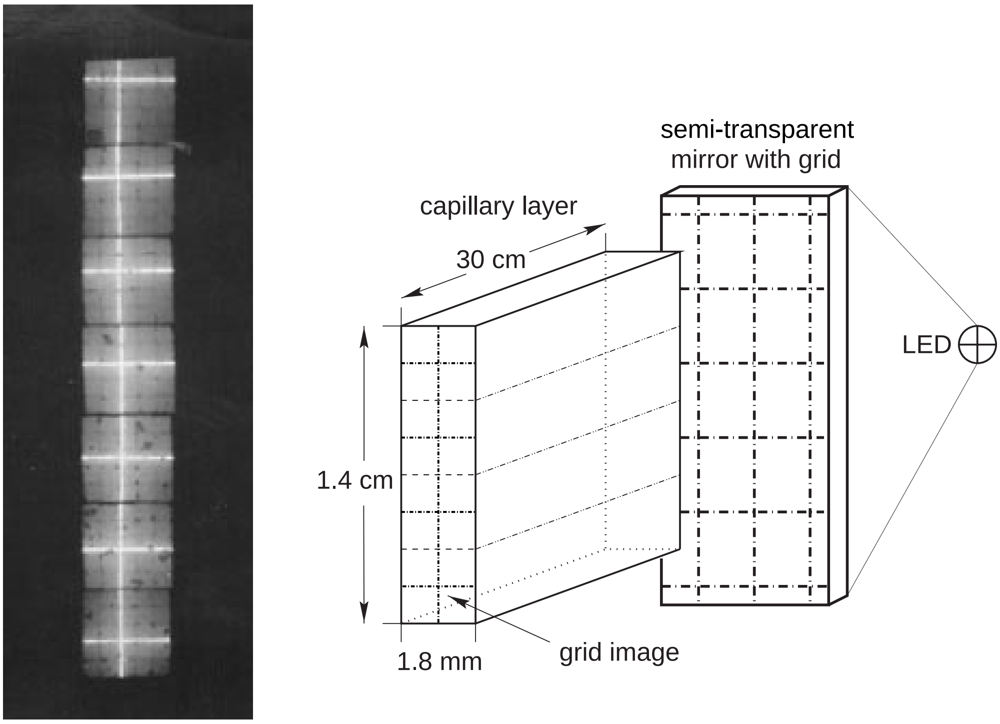

Figure 10: Picture of the fiducial grid as seen through a filled capillary layer to assess array uniformity. The lines on the grid are spaced 2 mm.

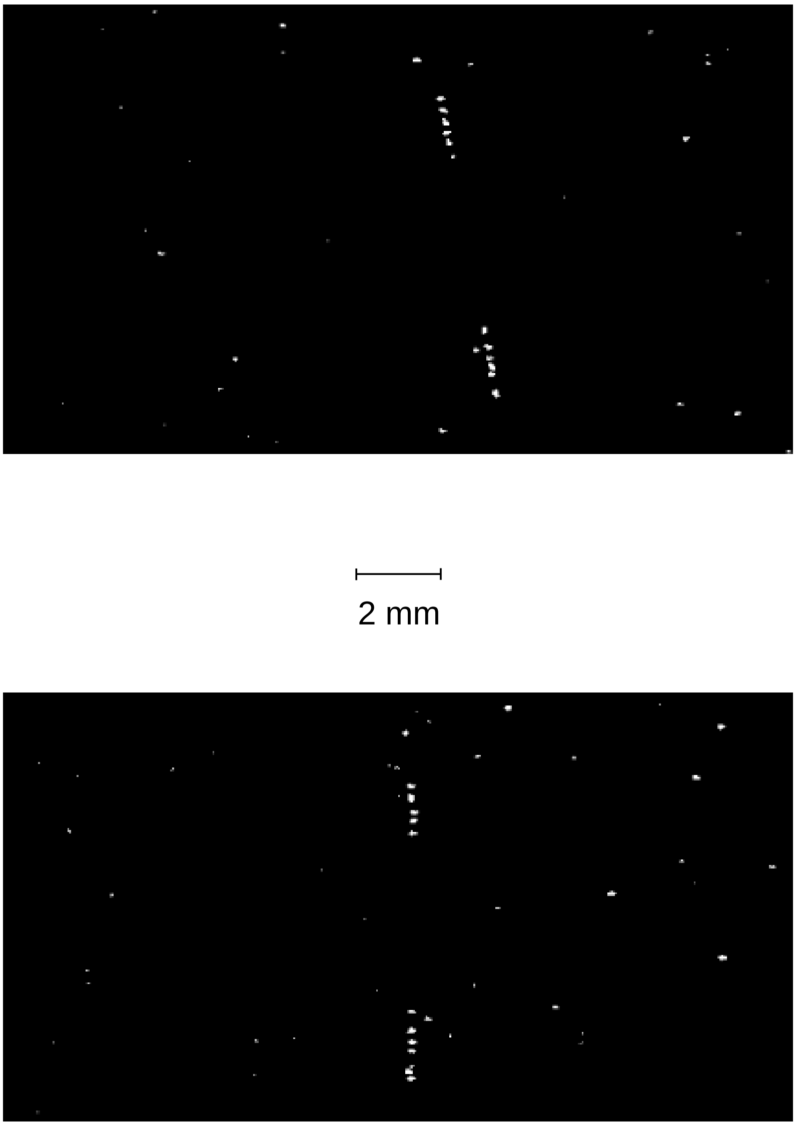

Figure 11: Two cosmic ray events illustrating the “minivector” detection in two capillary layers.