# Charged-particle tracking with high spatial and temporal resolution using capillary arrays filled with liquid scintillator

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## ABSTRACT

We have developed a new technique that allows the trajectories of ionizing particles to be imaged with very high spatial and temporal resolution. This technique, developed for future experiments in high-energy physics, may also be applied in other fields. Central to the technique is a detector consisting of a bundle of thin, glass capillaries filled with a liquid scintillator of high refractive index. These liquid-core scintillating fibres act simultaneously as a detector of charged particles and as an image guide. Track images seen at the readout end of the capillary bundle are amplified by an optoelectronic chain consisting of a set of image-intensifier tubes and read by a photosensitive CCD camera. We report here on results obtained with detector prototypes. A spatial resolution of 6−14 $\mu$m, dependent on image magnification prior to readout, has been obtained with 16 $\mu$m capillaries. The high scintillation efficiency of the liquid scintillator used and a large light attenuation length – $\sim$3 m for 20 $\mu$m capillaries – result in hit densities along the track of a minimum-ionizing particle of 8.5 mm$^{-1}$ and 3.5 mm$^{-1}$ at distances from the readout window of $\sim$2 cm and $\sim$1 m respectively. The radiation resistance of the detector is an order of magnitude greater than that of other types of tracking device of comparable performance. To complement the detector we have been developing a new readout system based around a gateable Vacuum Image Pipeline (VIP) and an Electron-Bombarded CCD camera. These increase the spatial and temporal resolution obtained with the detector and render it particularly attractive as a microvertex detector for the observation of short-lived particles in high-energy physics experiments performed with elevated interaction rates.

KEYWORDS: High-resolution tracker, particle detector, glass capillaries, liquid scintillator, optoelectronic readout.

## 1. INTRODUCTION

Detectors based on plastic scintillating fibres have been succesfully operated in high-energy physics experiments. In such detectors, huge numbers of optical fibres having scintillating cores are packed together as bundles or superlayers. Scintillation light is captured in a fibre by total internal reflection at core-cladding boundaries, so that scintillating fibres act simultaneously as charged-particle detectors and as light guides. Track images formed at a bundle's readout end, are intensified by an optoelectronic chain consisting of a set of image-intensifier tubes and are recorded by a photosensitive Charge-Coupled Device (CCD). This readout system permits fast, real-time, non-repetitive imaging.

In the past few years various groups have contributed to the development of a new particle-detection technique based on the use of liquid-core scintillating fibres – that is, thin, glass capillaries filled with liquid scintillator (LS) [1–9]. We have been working in this area for several years and have recently achieved significant progress in terms of bundle coherence, attenuation length and light yield. We are additionally developing a new readout chain based on a gateable Vacuum Image Pipeline (VIP) [10–12] and an Electron-Bombarded CCD camera (EBCCD) [6]. These novel devices increase the spatial and temporal resolution obtained with the detector and permit its use at very high rates when only a small fraction of detected images is to be recorded and analysed.

The primary aim of our research is the construction of detectors for high-precision tracking in high-energy physics experiments, but the technique of real-time, high-resolution, non-repetitive imaging may also have interesting applications in the contexts of astronomy, biology and medical diagnosis. In high-energy physics the technique being developed is particularly relevant to neutrino experiments, experiments at a high-luminosity collider and fixed-target experiments, in all of which emphasis is placed on the detection of short-lived particles.

A microvertex detector to be used at a future collider or in a fixed-target environment should be characterised by:

- a high level of granularity, this resulting in a compact device of high spatial resolution;
- good track reconstruction and vertex identification capabilities;
- fast response (integration time less than 20 ns) and triggerability;
- low sensitivity to gamma-rays;.
- high radiation resistance.

Similarly, a tracking detector for neutrino physics, especially one for $\nu_\tau$ physics, should provide high spatial resolution (better than 20 $\mu$m) and high hit densities over an extensive volume, this necessitating a large number of detector elements.

The novel technique based on the use of coherent arrays of small-diameter glass capillaries (in the range $10 - 30$ $\mu$m) filled with newly synthesised liquid scintillators, offers excellent spatial resolution and is extremely promising. The much improved light transmission of liquid-core fibres has made viable the construction of detectors of extended volume. Readout of the fibres is possible using optoelectronic components, which may form a cost-effective data-acquisition system able to deal in parallel with huge numbers of output channels. Exploiting the new form of image pipeline, the VIP, and the high radiation hardness (to the order of 100 Mrad) of certain liquid scintillators makes possible applications in high-luminosity experiments .

An extensive R&D program covering the areas outlined above has recently been recommended by the LHC committee at CERN [13]

Our recent results concerning the development of the new readout devices – the EBCCD and the

VIP – are the subject of other contributions to this conference.

Here we explain the principles of operation of the detector, describing the detector components and the performance levels achieved, referring to the results of various laboratory tests as well as to beam tests of detector prototypes. In particular we report on preliminary results obtained in a Pilot experiment [8], carried out with a prototype installed upstream of the Chorus [14] detector in the Cern Wide Band Neutrino Beam.

## 2. REASONS FOR CHOOSING CAPILLARIES

Scintillating fibre detectors may be built using glass fibres, plastic fibres, or glass capillaries filled with organic liquid scintillator [1]. The latter effectively combines advantages of glass and plastic fibres, for example, the fast time response (of the order of a few nanoseconds [7]) of plastic fibres, and the reduced levels of optical cross-talk characteristic of glass fibres when used with an extra-mural absorber. In addition, glass capillaries filled with liquid scintillator are able to offer high light yields and long light-attenuation lengths ($>$ 2 m for capillaries of $\sim$ 20 $\mu$m diameter) [6, 8]. For minimum-ionizing particles traversing $\sim$20 $\mu$m capillaries at distances from the capillaries' readout ends of $\sim$2 cm or $\sim$1 m, the hit densities currently recorded are respectively $\sim$8.5 mm$^{-1}$ and $\sim$3.5 mm$^{-1}$ .

The time resolution of a scintillating-fibre based detection system is determined by the scintillator decay time, which is typically between 3 ns and 7 ns for the liquids used [7,15], by the temporal dispersion of the light signal that propagates along the fibres, and by the time response of the optoelectronics.

Liquid-core fibres also have the advantage of being able to tolerate large radiation doses without significant degradation of performance.

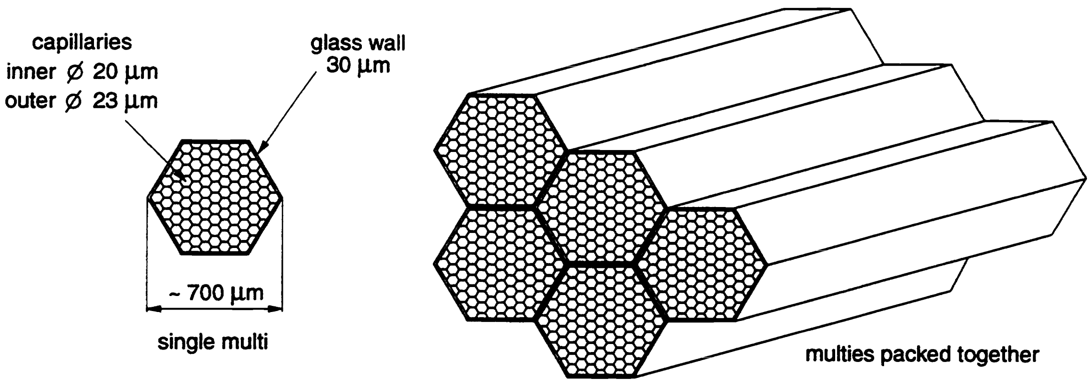
## 3. PRODUCTION OF CAPILLARY BUNDLES

The production of a bundle starts with the manufacture of glass tubes of 1-2 mm diameter. These are stacked in groups of several hundreds, then thin rods of black glass, which constitute the extra-mural absorber, are inserted in the inter-capillary gaps. This construction is drawn at high temperature to give a multi-capillary bundle (multi). Bundles of this type are packed together and drawn again to give the final array of narrow capillaries. The technique is now well developed in commercial companies such as Schott[1].

Capillaries are drawn from borosilicate glass of refractive index $n$ = 1.49. Using a diamond saw, the end faces of the fully assembled bundle are carefully cut so as to produce a planar surface that may be coupled to an optoelectronic readout system. Various detectors of moderate dimensions have been constructed using capillaries having diameters ranging from 15 to 75 $\mu$m [2–6]. These have been tested with diverse readout procedures and the capillary arrays have exhibited excellent uniformity. More recently larger-volume bundles have been produced by Schott using innovative methods and the properties of these bundles are investigated in an on-going study. Fig. 1 shows an example of a bundle structure based on hexagonal multies.

The prototype large-volume bundle used in the Pilot experiment [8] is an array composed of more than $5 \times 10^5$ capillaries having inner and outer diameters of 20 $\mu$m and 23 $\mu$m respectively. Each multi consists of 547 capillaries, arranged as a structure having a cross-section in the form of an equilateral

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




Schott borosilicate glass 8250

| | |
|---|---|
| density | 2.28 g cm$^{-3}$ |
| radiation length | 12.4 cm |
| refractive index | 1.49 |
| thermal expansion | $5\times10^{-6}$ K$^{-1}$ |
| transformation temp. | 492 °C |
| softening point | 715 °C |

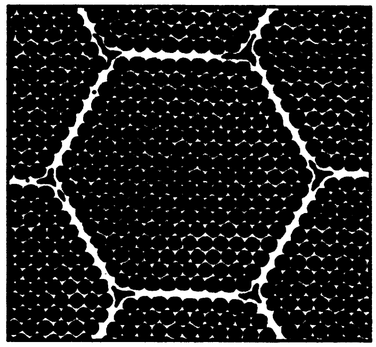


Figure 1: Structure of a large-sized bundle based on hexagonal multies. The lower right-hand section shows a photograph of the end face of a capillary bundle.

hexagon and enclosed in a glass wall having a thickness of about 30 $\mu$m. The packing fraction, defined as the ratio of the capillaries' open area to the area of a multi's cross-section, is $\sim$ 55 %. The complete module is composed of 940 multies stacked together in a glass tube of $2 \times 2$ cm$^2$ cross-section and of 1.8 m length. The end of the bundle to be coupled to the readout chain is tapered so that it will magnify event images before they arrive at the first image intensifier. The core diameter of each capillary smoothly increases near its readout end from 20 $\mu$m to 34 $\mu$m, and the target dimensions increase from $2 \times 2$ cm$^2$ to $3.4 \times 3.4$ cm$^2$.

A new large-sized bundle, produced by Schott and now being tested, consists of some 1385000 capillaries of 25 $\mu$m diameter and has a packing fraction of $\sim$ 70 %.

## 4. LIQUID SCINTILLATORS

Capillary bundles are filled with liquid scintillator either by taking advantage of the capillarity or by applying a small overpressure. Many combinations of solvents and dyes have been tested [1–9]. The main requirements for the solvent include:
- high transparency;
- high radiation resistance;
- high refractive index, to maximize the efficiency for trapping light via total-internal reflection at

the liquid-glass interface.

The solvent used in most of the liquid scintillators currently considered is 1-methyl-naphthalene (1MN), which has a refractive index of 1.62 and, in capillaries of borosilicate glass, gives a light-trapping efficiency of 7.7 % in each direction.

The principal requirements for the fluorescent dye are:
- high scintillation efficiency;
- local light emission (important to optimize the spatial resolution with small-sized capillaries);
- large Stokes shift to reduce self-absorption;
- emission spectrum well matched to the region of sensitivity of the photodetector;
- high radiation resistance.

Best results so far have been obtained with the newly synthesised dyes[2] R39, R45, 3M15. All of these dyes have emission spectra that peak at wavelengths in the green region ($\sim$ 500 nm) and for which relatively efficient image-intensifier photocathodes are available. Liquid scintillators that emit in the green region are also of interest because of their enhanced radiation hardness.

## 5. LIGHT YIELDS AND ATTENUATION LENGTHS

Interest in capillary detectors is stimulated by their outstanding performance in terms of light yield and attenuation length. As well as the considerable progress made in producing efficient liquid scintillators of high refractive index, the quality of the liquid-glass interface has been improved. This results in reduced reflection losses and, even in small diameter capillaries, the light-transmission properties are excellent.

For a liquid scintillator consisting of 1MN doped with the new dyes mentioned above the scintillation efficiency is 20–50 % higher than that of a conventional plastic scintillator [7]. Further, the trapping efficiency of liquid-core fibres is 40 % larger than that of standard polystyrene-based fibres. With a bundle having a packing fraction of 63 %, filled with 1MN+R39, a hit density of 8.5 $mm^{-1}$ has been measured along the tracks of minimum-ionizing particles that traverse the bundle $\sim$2 cm from its readout end [6]. For comparison, the corresponding hit density for SCSF38 plastic fibres having a diameter of 0.5 mm and a packing fraction of 90 % is 4.6 $mm^{-1}$.

The purity of solvents and dyes has been found to greatly affect the experimental results. As an example, we show in Fig. 2 the attenuation curves measured for a liquid scintillator based on 1MN for two different levels of purification. After the initial, severe attenuation, essentially due to the absorption of the light of shorter wavelengths, the attenuation is almost exponential.

An attenuation length of about 4 m is obtained for 0.5 mm capillaries filled with the highly purified liquid scintillator. To appreciate the amount of progress achieved one may compare with the pioneering measurements where attenuation lengths of no more than a few centimetres were recorded.

Given the high reflectivity of the liquid–glass interface, the attenuation length in a capillary having a diameter as small as 20 $\mu$m is not very much different from that of a larger diameter capillary. In the Pilot experiment, with the bundle described in section 3, consisting of capillaries of 20 $\mu$m pore filled with 3 g/l of 3M15, an attenuation length of $\sim$3 m was measured (Fig. 3). This translates into a hit density of $\sim$ 3 $mm^{-1}$ for particles crossing the bundle end furthest from the readout photocathode and is substantially better than that achieved with small diameter plastic fibres.

[2]Geosphaera, Ul. M. Ulianova 16, Moscow, 117 133, Russia. Telefax: +7-501-883-3006.

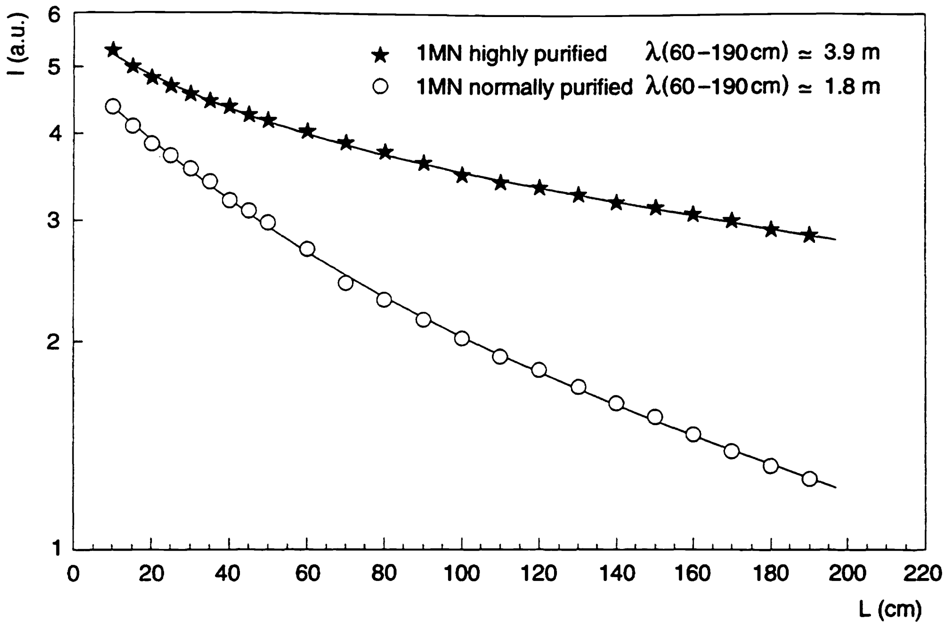



Figure 2: Influence of the purity of the solvent (1MN) on the light-attenuation length measured in 0.5 mm single quartz capillaries activated by a radioactive source. The scintillating dye, 3 g/l R45, is the same in the two cases considered.

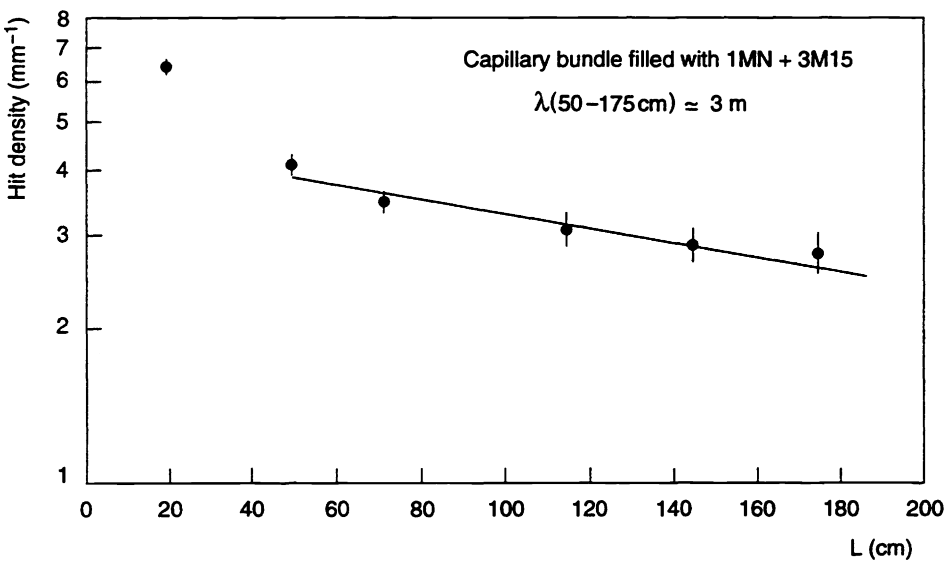



Figure 3: Hit density as a function of the distance L from the photodetector, measured in a 5 GeV/$c$ hadron beam, at the Cern proton synchrotron, for the prototype large-volume bundle filled with 1MN doped with 3 g/l of 3M-15.

## 6. RADIATION RESISTANCE

Measurements performed for many liquid scintillators [9,16] demonstrate that, in some cases, the scintillation efficiency and transmission characteristics are affected only slightly by exposure to very high radiation doses. For example, the scintillation efficiency of 1MN doped with R39 decreases by 10 % for a dose of 60 Mrad and by 30 % for a dose of 190 Mrad (Fig. 4). Darkening of capillary glass

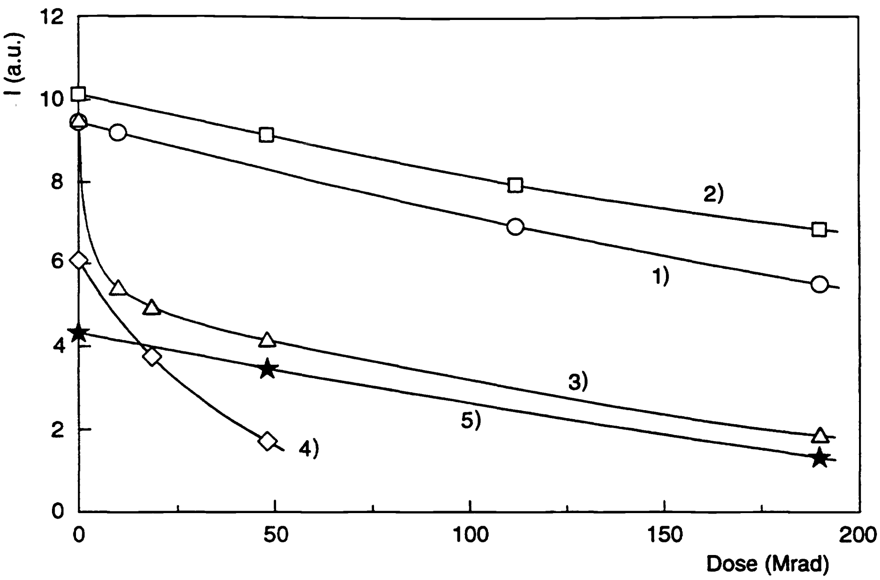



Figure 4: Light output as a function of the radiation dose, for different liquid scintillators: 1) MN+R6; 2) 1MN+R39; 3) 1MN+R45 by Geosphaera, and 4) BC-599-13G; 5) BC-599-13B by Bicron.

by radiation does not greatly affect the attenuation length of light in capillaries because the change in reflectivity at the scintillator-glass interface is small. According to our estimates, capillary detectors can tolerate radiation doses as long as the light-attenuation length in the capillary glass remains larger than a few centimetres (for a capillary length $\geq$ 1m). Any optoelectronic readout system will be much more susceptible to radiation damage, but may be installed far from regions where radiation doses are highest.

## 7. OPTOELECTRONIC READOUT AND TRIGGER SYSTEM

Event images transmitted to the end face of a capillary bundle are faint – the typical light output is of the order of 1 photon per minimum-ionizing particle per capillary traversed – and the images must be amplified before they may be recorded by a position-sensitive photo-receiver such as a CCD. The amplification ( $\times 10^4 - 10^5$) is commonly provided by a series of image intensifiers (II), the technology of which is well understood. Typically the first stage is an electrostatically focused tube characterised by relatively small gain but high spatial resolution and low noise. This element of the readout system is the most critical for the detector efficiency and should have a high quantum efficiency ($\geq$ 20%) and good transmittance at the fibre-optic entrance window. The main image amplification is performed by an II tube that contains a microchannel plate (MCP). The optoelectronic chain used in the Pilot experiment is shown in Fig. 5. The image is initially magnified, so as to compensate the relatively poor spatial resolution (25 line pairs per mm) of the MCP, and subsequently demagnified by a further electrostatically focusing II so as to fit onto a Megapixel CCD (Thomson TH7896 [3]).

In most high-energy physics experiments only a small fraction of the detected events is of interest

[3]Thomson, Division Tubes Electroniques, Boulogne-Billancourt,France.

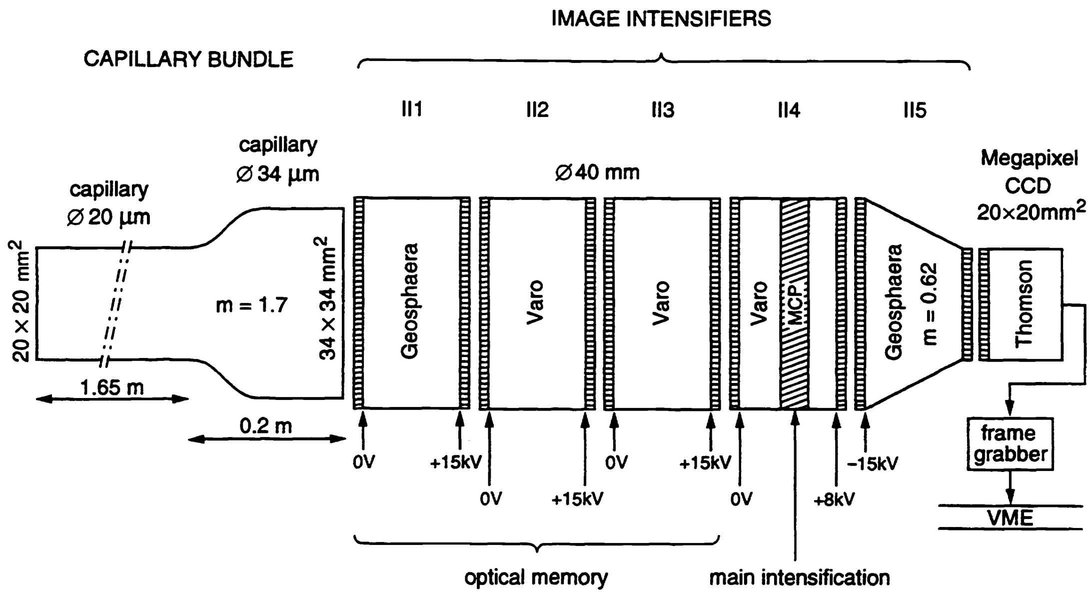



Figure 5: Scheme of the optoelectronic chain used in the Pilot experiment.

and, given band-width limitations, it becomes necessary to make trigger selections. First-level trigger decisions are usually available within 0.1-1 $\mu$s of the occurrence of an event. Images from a capillary bundle need to be delayed for a similar amount of time, so that the decision may be taken as to whether or not the event should be recorded via the CCD.

In conventional readout systems, consisting of a set of IIs followed by a gateable proximity-focused tube containing an MCP and by a CCD [4–6, 8], readout triggering is performed at the MCP level by applying a gate pulse (typically 200 V). The delay needed for the trigger is provided by the image persistence associated with the decay times of the image-intensifier phosphors preceding the MCP. This persistence defines the maximum event rate allowed before images from consecutive events become superimposed on one another.

Phosphors with long decay times and good efficiency are available, but their use severely limits event rates. The fastest available phosphor (P47) has a decay time of $\sim$ 35 ns. If one uses a chain of several IIs equipped with this phosphor it is possible to have a delay of about 100 ns and a time resolution of the same order. This configuration, which requires a fast trigger decision, can be used for event rates up to about $10^6$ $s^{-1}$.

For many applications a time resolution much shorter than the trigger decision time is needed. In view of this we have been developing the Vacuum Image Pipeline (VIP) [12, 13], which is capable of introducing image delays of the order of a few microseconds with a time resolution of the order of 10 ns.

Readout times for CCDs are typically of the order of several milliseconds. For special applications, a higher-level trigger on the CCD can be implemented if the CCD offers the possibility of performing a "fast clear" or a "memory dump".

## 8. SPACE RESOLUTION

In the absence of problems relating to non-local emission of scintillation light and to cross-talk, the spatial resolution of a capillary-based detector is determined by the capillary diameter, the uniformity of the capillary array and the characteristics of the readout system.

Images of the tracks of minimum-ionizing particles recorded in beam tests have been analysed. Each single, isolated photoelectron is detected as a spot formed by a cluster of CCD pixels registering a pulse height above some threshold. The spot size measures the intrinsic resolution of the readout chain after the first II and contributes to the detector's "two-track resolution". A straight-line fit to cluster barycentres is performed after correcting for small distortions introduced by the optoelectronic readout system. The value of the "track residual" is dependent on the capillary diameter, the uniformity of the capillary array and the resolution of the first II of the readout chain.

Many measurements have been made for small-sized bundles. For a bundle having a cross-section of 25 $mm^2$ and consisting of capillaries of 16 $\mu$m pore diameter, a track residual of $\sigma_{tr} = 14$ $\mu$m and a two-track resolution of $\sigma_{tt} = 33$ $\mu$m were determined [6]. To reduce the contribution to the spatial resolution of the optoelectronic chain, a capillary bundle with a tapered end (a capillary taper) was used to magnify the image transmitted to the first II. With a taper magnification of $\times 4.7$, a value of $\sigma_{tr} = 6$ $\mu$m (Fig. 6a), close to the intrinsic limit defined by the capillary diameter, was obtained. It should be noted that the value quoted represents the resolution for single coordinates - track impact parameters are determined with much greater precision.

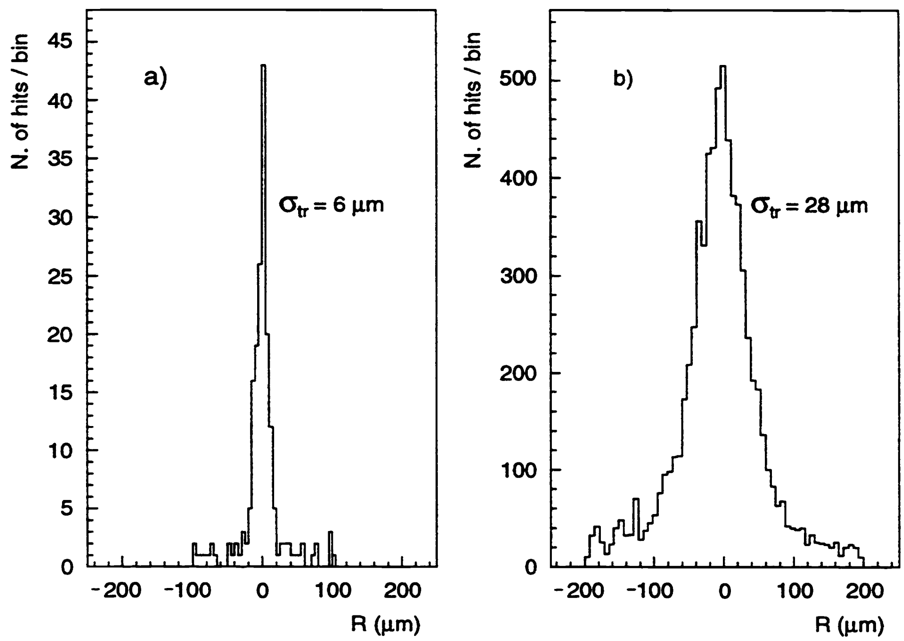



Figure 6: Distribution of track residuals R, measured for a): a small sized capillary bundle of 16 $\mu$m capillary pore diameter, tapered with magnification 4.7; b): a large volume capillary bundle of 20 $\mu$m capillary pore diameter, tapered with magnification 1.7.

For the large-sized bundle of the Pilot experiment that, as previously described, is tapered to give a magnification of $\times 1.7$, a root-mean-square (RMS) residual of 28 $\mu$m was measured (Fig. 6b) for the tracks of particles crossing at considerable distances from the readout location. This value is a few times the intrinsic limit and reflects the non-perfect uniformity of the bundle. For single photoelectrons the RMS spot size was 18 $\mu$m in real space. Modified bundle-assembly procedures, intended to improve the array uniformity, are being studied. A new detector, which pairs a bundle of higher quality and a completely revised readout chain, based around a megapixel EBCCD by Geosphaera, is under construction, the aim being to achieve better resolution, and will be tested on beam later this year.

## 9. TRACKING PERFORMANCE

The tracking capabilities of a detector based on liquid-core scintillating fibres are well illustrated by the preliminary results of the Pilot experiment, where the image given by $5 \times 10^5$ capillaries is seen by $10^6$ CCD pixels. An example of a multi-track event is shown in Fig.7 and evidences the outstanding performance in terms of resolution and hit density.

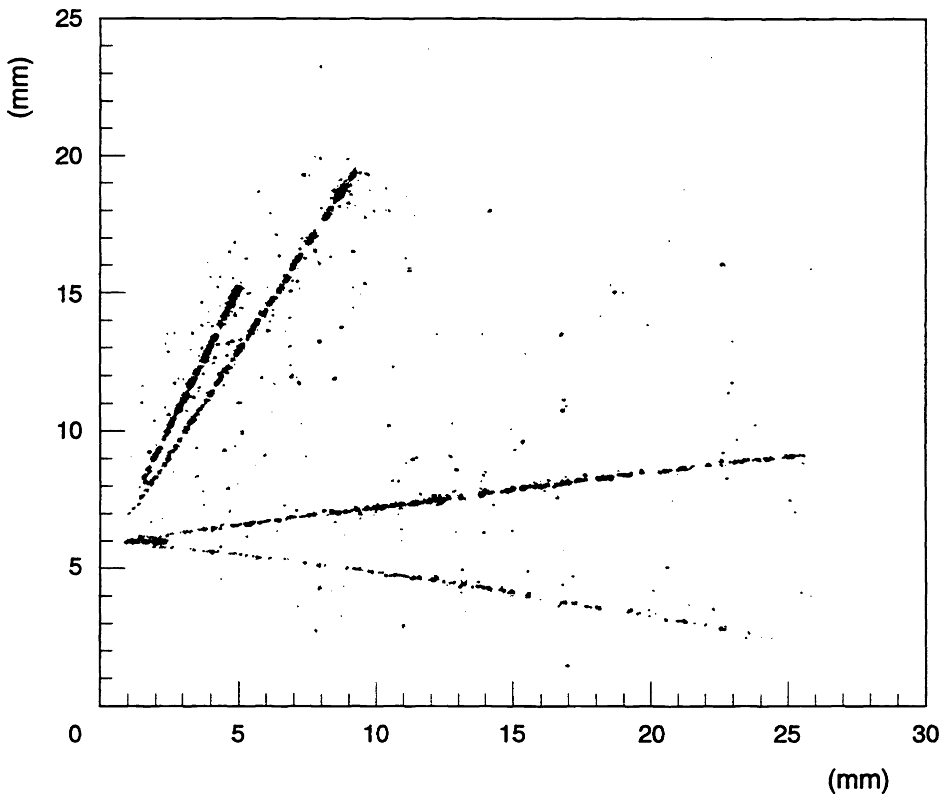



Figure 7: Image of a neutrino interaction in the first large volume prototype. The neutrino beam enters from the side of the bundle. Event occurred in the tapered part of the bundle, where the capillary diameter is 34 $\mu$m.

The interaction shown occurred in the tapered part of the capillary bundle, near to the readout end, where the capillary diameter is 34 $\mu$m. The measured track residual is $\sigma_{tr} = 15$ $\mu$m and the hit density is $\sim$8 mm$^{-1}$. These figures compare favourably with those obtained using other techniques. Hit densities typically recorded with silicon-microstrip detectors, for example, are significantly less than 1 mm$^{-1}$. In fact capillaries filled with liquid, yield $\sim$2500 hits per radiation length of material traversed, almost an order of magnitude greater than that achieved with silicon detectors, and also significantly larger than that given by gas chambers.

Being able to obtain increased amounts of information with small quantities of radiating material introduces new possibilities for vertex detection in high-energy physics. Our research-and-development program foresees the construction of thin layers of capillaries that will not only measure coordinates on the paths of traversing particles but will record track vectors. For a detector formed from such capillary layers, the identification of corresponding track segments in different detector sections allows a high reconstruction efficiency and a minimization of ambiguities. Fig. 8 shows, for a single simulated event, the tracks that would be recorded in two layers of capillaries as compared to the tracks that would be seen in a silicon-microstrip detector, the amount of radiating material in the two cases being comparable.

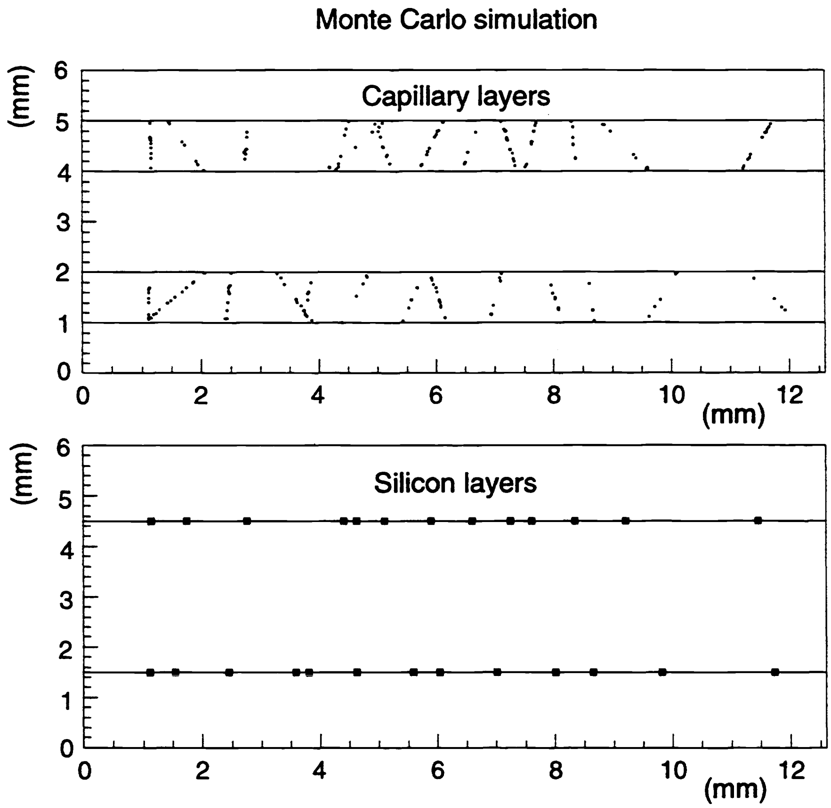



Figure 8: Monte Carlo simulated tracks in two capillary layers (1 mm thick) and in two layers of semiconductor microstrip detectors. In the case of capillaries, track vectors can be easily determined.

## 10. CONCLUSIONS

We are developing a particle-tracking detector based on thin capillaries filled with liquid scintillator. The main advantages of this detector are:

– good spatial resolution ($\sim$10 $\mu$m);

– high hit density ($\sim$2500 hits per unit radiation length, almost an order of magnitude better than that achieved with silicon-microstrip detectors);

– excellent radiation resistance (up to $\sim$ 100 Mrad).

The optoelectronic devices used in readout allow:
- multiplexing of a huge number of channels

The new image-delay technique, based on the use of the VIP, currently being developed, offers:
- high time resolution (~10 ns)
- possibility of operating at high event rates (~$10^7$-$10^8$ Hz)

Capillary-based detectors may solve many of the technical problems of future experimentation in high-energy physics. The micro-imaging technique we are developing also has a potential for applications in other fields, for example astrophysics and medical diagnosis, and there is the possibility of industrial spin-offs.

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