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A new vertex detector made of glass capillaries

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Abstract

We have developed a new detector technique that allows high quality imaging of ionizing particle tracks with very high spatial and time resolution. Central to this technique are liquid-core fibres of about 20 μm diameter read out by an optoelectronic system including a CCD. The fibres act simultaneously as target, detector and light guides.

A large-volume prototype, consisting of 5×10^5 capillaries of 20 μm diameter and 180 cm length, has been tested in the CERN wide-band neutrino beam. A sample of high-multiplicity neutrino interactions was recorded, demonstrating the imaging quality of this detector. First results from the reconstruction of these events are reported. A track residual of 28 μm and a vertex resolution of 30 μm has been achieved.

Future applications of capillary detectors for neutrino and beauty physics are being investigated within the framework of the RD46 collaboration.

1. Introduction

Nowadays scintillating fibres have found wide applications in high energy physics, mainly for tracking and calorimetry.

Scintillating fibre detectors can be made using glass, plastic or capillaries filled with liquid scintillator [1]. Plastic fibres exhibit a fast response, of the order of a few nanoseconds, and a high light yield. The performance achieved with plastic fibres is however limited by the technological difficulty in producing very thin fibres with long attenuation lengths (for 60 μm fibres an attenuation length of about one metre was obtained). Another problem with plastic is the presence of optical cross-talk due to the difficulty of surrounding the fibres with an absorber material (extra-mural absorber EMA) which does not diffuse into the fibres.

Glass fibres, where the core is made of a specially doped glass (e.g. Ce), have a high radiation resistance and light-absorbing glass can be inserted to eliminate optical cross-talk. They have however a slow time response and the achieved attenuation lengths are only of the order of centimetres.

Glass capillaries filled with liquid scintillator combine the advantages of plastic fibres and glass fibres, while, in addition, their excellent core/cladding reflectivity (light loss per reflection $\approx 10^{-6}$) allows long attenuation lengths even in thin (20 μm) fibres. Due to the possibility of introducing an interstitial absorber, optical cross-talk is

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small. The small fibre diameter combined with an appropriate readout resolution provides high spatial resolution. Nowadays, liquid scintillators exist with a light yield significantly larger than the one in plastic fibres [2], attenuation length of about 3 m in 20 μm diameter [3]. Moreover they are extremely radiation resistant [4].

Within the last three years our collaboration [9] has made considerable progress in the development of large capillary bundles and liquid scintillators [2–8]. This development provided the basis for the first application of a capillary detector prototype in a neutrino beam, which is described in the following and has led to a proposal for continued R&D under way at CERN under the name RD46 [8].

2. Development and testbeam results

The detector consists of a coherent bundle of glass capillaries filled with an organic liquid scintillator [1,3,5], a binary system consisting of a solvent and a scintillating dye, whose concentration is optimized to maximize light output and attenuation length. A passing charged particle creates scintillating light in the liquid core which is emitted isotropically along the particle's path, as schematically shown in Fig. 1. A fraction of the light (about 7%, in one direction, in the case of $n_{clad} = 1.49$ and $n_{core} = 1.62$ for 20 μm capillaries) is captured and transmitted along the fibre by total reflection.

The scintillation efficiency is determined by the liquid scintillator properties and the efficiency of the light transmission which can be affected by reflection losses and self-absorption. The strong influence of the purity on the light attenuation has been demonstrated for the solvent as well as for the scintillating dye [3]. With a liquid scintillator composed of the highly purified components 1 MN + 3M15 [a], an attenuation length of 393 cm was achieved in 500 μm quartz capillaries and about 300 cm in 20 μm borosilicate capillaries.

Studies of the radiation resistance up to doses of 180 Mrad have been reported in Ref. [4]. Some of the scintillating mixtures, e.g. 1MN + R6 and 1MN + R39 are very stable, the light output is still 70% at 180 Mrad.

Various prototypes have been built and tested in a pion beam. Several thousands crossing tracks were recorded and used to evaluate their performance. The hit density is about 8 hits/mm at short distances from the readout and 3 hits/mm [3] at one metre from the readout.

The spatial resolution of a capillary detector is determined by the capillary diameter, the bundle uniformity, the magnification of the image at the entrance of the readout chain and the readout resolution. For a small cross-section bundle (25 mm^2) composed of 16 μm diameter capillaries and an image magnification of 4.7 before the readout chain, a track residual of $\sigma = 6$ μm has been measured [10]. The large magnification makes the contribution of the readout to the overall resolution negligible and a value close to the theoretical limit determined by the capillary diameter is obtained. For the large-volume target described in Section 3 (dimensions are $2 \times 2 \times 180$ cm^3) composed of 20 μm capillaries and a modest magnification of 1.7 before the readout, a track residual of 28 μm, averaged over the entire bundle length of 180 cm, has been measured [3]. This is about three times the theoretical limit as expected from the capillary diameter of 20 μm alone. The worsening of the resolution is due to a larger contribution of the readout to the overall resolution and the non-perfect uniformity of the larger size bundle.

For the first time, long-term studies of the liquid scintillator stability were possible. The construction of the bundle endcaps is such that contact with oxygen is avoided. It is known that dissolved oxygen gives rise to unwanted energy transfer processes [10] which reduce the light output.

A first measurement of the attenuation length of 1 MN + 3M15 in the 20 μm capillaries of the prototype was performed in a 5 GeV pion test beam where about 300 cm

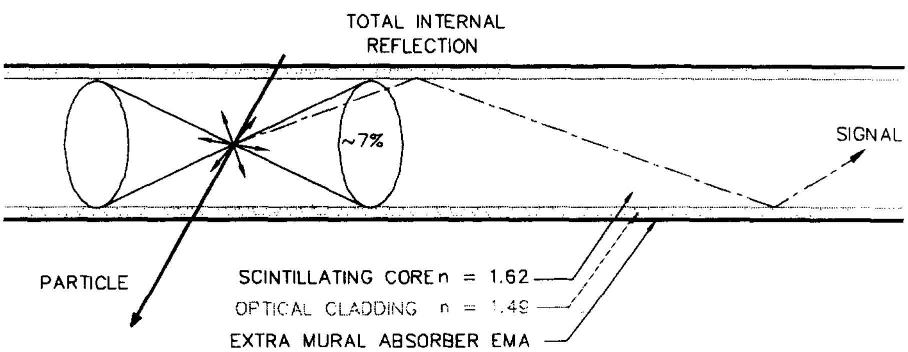


Fig. 1. Principle of light transmission in a capillary.

was obtained. For the application in the neutrino beam the target was cleaned and refilled, and has then been constantly in place since June 1995. The attenuation length has been measured regularly. No degradation in the attenuation length is observed in one year.

3. First application in a neutrino beam

3.1. The prototype target

To investigate possible applications in neutrino physics (related to the detection of short-lived particles like charmed mesons and tau lepton), a large-volume bundle ($700\,cm^3$) has been built in cooperation with SCHOTT [b]. The bundle structure is based on small hexagonal bundles, so-called multies, which are fused together to reach cross-sections of several square-centimetres.

The prototype consists of 5×10^5 borosilicate capillaries of 20 μm diameter forming a bundle with $2 \times 2\,cm^2$ cross-section and 180 cm length. At the readout-end the diameter of each capillary and the overall bundle cross-section increases by a factor 1.7 thus magnifying the image before entering the readout devices. The bundle is filled with the scintillation mixture 1 MN + 3M15.

A special system at the bundle end ensures optical contact between target and readout, which is necessary since any air gap or bubble would cause major light scattering and loss of resolution. To evaluate the distortion introduced by the bundle and the optoelectronic chain, a reference grid is placed at the opposite side of the bundle and may be imaged on the CCD by a LED illumination system. At the same bundle end a reservoir-tube contains a small amount of additional liquid scintillator to compensate volume variations of the liquid scintillator with temperature.

3.2. The readout

The large number of capillaries requires an integrated readout provided by a position sensitive Charge-Coupled-Device (CCD). Its low intrinsic gain requires a pre-amplification of the single photons emerging from the capillaries to get a sufficient signal-to-noise ratio.

The prototype is read out by an optoelectronic chain, shown in Fig. 2, consisting of five image intensifiers. After pre-amplification in the first three electrostatically focusing stages, the main intensification takes place in a micro-channel plate which may be gated by an external trigger. The phosphors of first stages serve furthermore as a memory to store the image until the trigger decision is taken. The last stage projects the amplified image onto the $2 \times 2\,cm^2$ surface of a Megapixel CCD [c] made up by 1024×1024 pixels of dimensions $19 \times 19\,\mu m^2$.

3.3. Objective of the measurement

The test in the neutrino beam is aiming at the application of the capillary technique for future ν_τ search – produced either through the oscillation mechanism or via D_S-decay at LHC-energies [1,16]. In both cases the short-lived tau-lepton ($\tau_\tau = 2.95 \times 10^{-13}$, $c\tau = 88.6\,\mu m$ [14]) has to be detected. The tau decays in 85.5% of the cases into a single charged lepton or hadron. Together with the missing momentum from the produced neutrino(s) a typical kink-signature is observed on which basis a ν_τ-interaction can be discriminated from the large ν_μ-induced background. The transverse impact parameter of the decay prong with respect to the primary interaction vertex is on

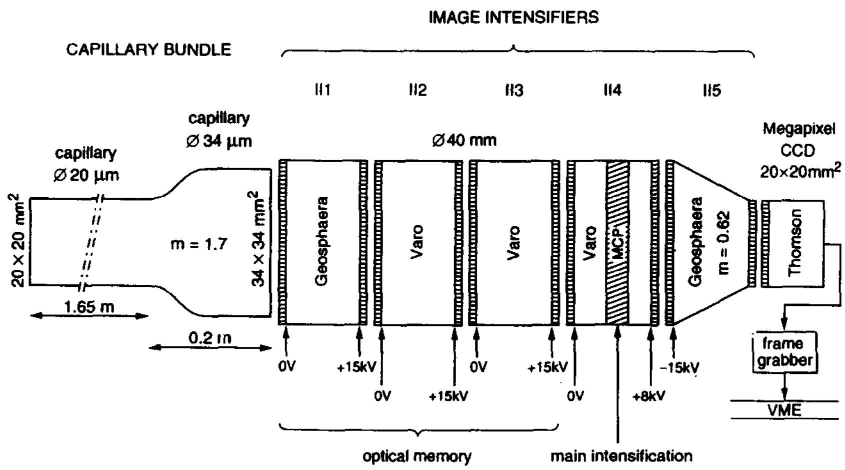


Fig. 2. Optoelectronic readout chain consisting of five image intensifiers and a Charge-Coupled-Device (CCD).

average 70 μm and a capillary detector of 20 μm resolution would be a suitable technique.

Our measurement will possibly allow us to study the reconstruction efficiency for multi-prong events and to evaluate the detection efficiency of short-lived particle decays (like charmed particles).

The target is installed in the neutrino beam, in front of the CHORUS [13] detector, as shown in Fig. 3. It is oriented vertically with the optoelectronic chain below the level of the CHORUS trigger volume in order not to affect the CHORUS trigger rate.

3.4. The set-up

The capillary target has a local trigger system based on two downstream scintillator counters and a third counter one metre upstream (Fig. 4). The use of different coincidence logics allows us to select crossing beam muons for calibration purposes or neutrino interactions. The local trigger decision is done within ≈120 ns. The event selection, according to the trigger decision, is done by gating the micro-channel plate and the CCD camera. The gate length, during which the light is integrated is 100 μs. For the neutrino trigger, the local capillary trigger is confirmed by the CHORUS trigger. The event is read out simultaneously by both detectors and the corresponding data are merged offline for a complete analysis.

The target has been calibrated and aligned with the CHORUS detector using about 10^5 muon tracks.

Given the small target mass (≈1.5 kg), the neutrino interaction rate is only about one per day. During 1.5 month data taking in 1995 about thirty-five neutrino interactions have been recorded and analyzed. This sample allowed us to develop analysis tools and to derive a first estimate of the vertex resolution. The statistics will be improved in the current 1996 run.

4. Experimental result

Some typical events of the capillary detector, which demonstrates its imaging capability, are displayed in Fig. 5. The neutrino beam is coming from the left side of the figure. The average charged track multiplicity of the observed neutrino interactions is 4.7.

Starting from the raw CCD picture as the one shown in

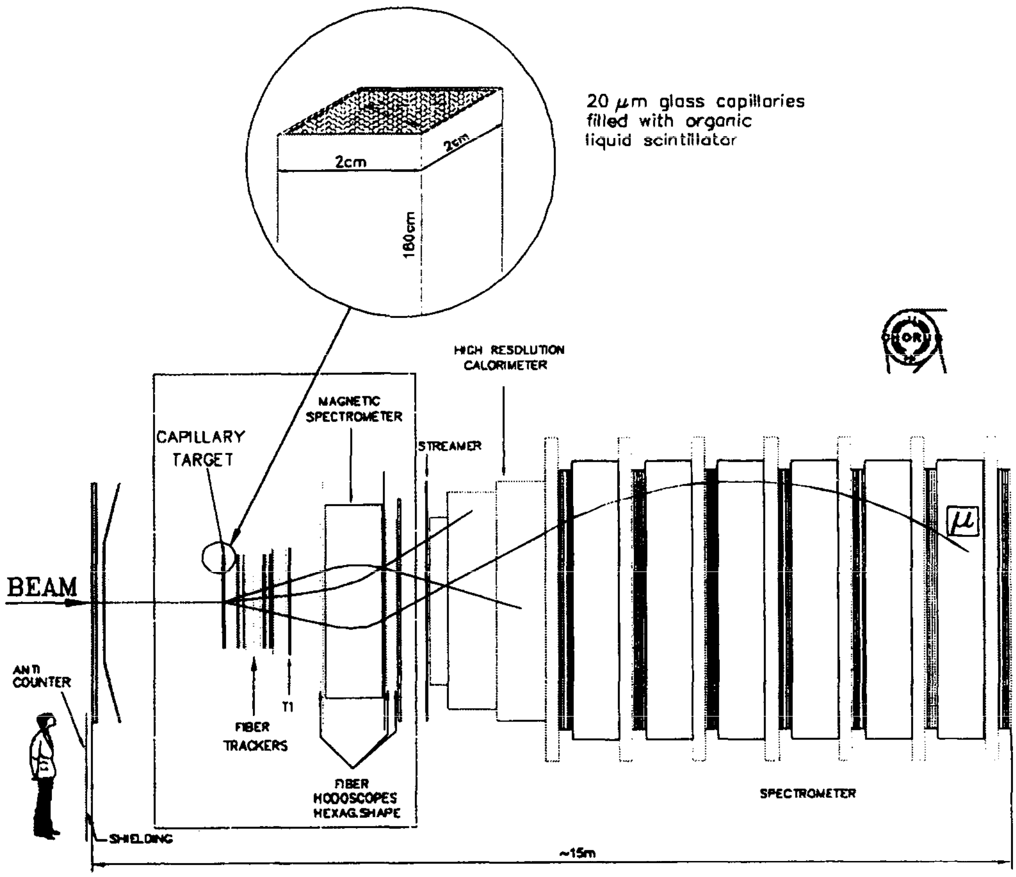


Fig. 3. The large-volume prototype within the CHORUS neutrino experiment.

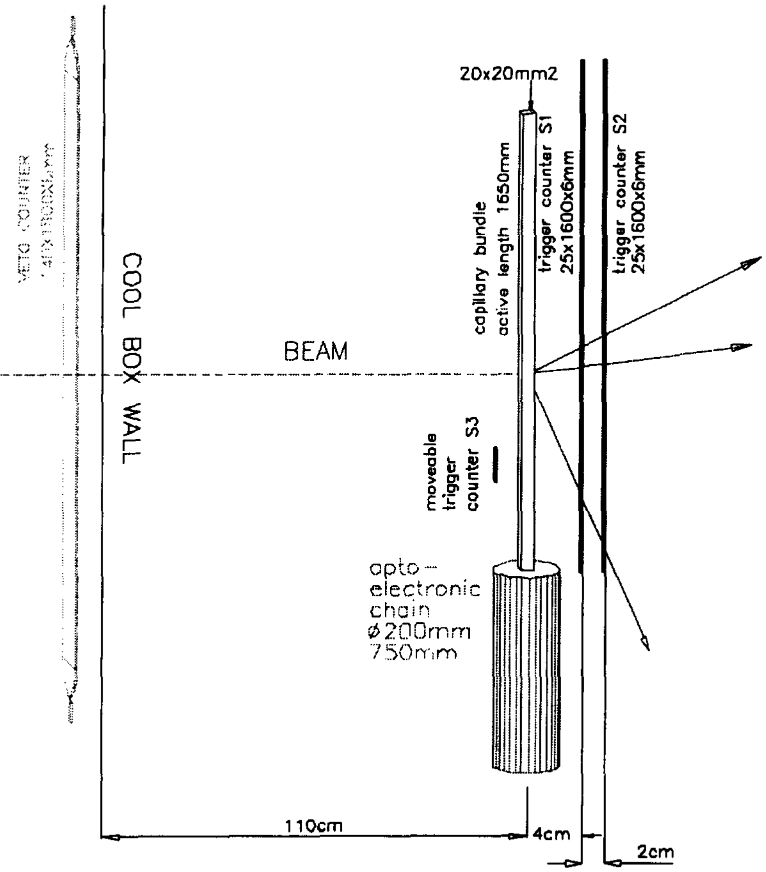


Fig. 4. Set-up of the capillary target including the trigger counters.

Fig. 6a, the analysis program searches for pixel-clusters, i.e. regions of adjacent active pixels as depicted in Fig. 6b. The local maxima of the pulse height distribution within each cluster defines the hit coordinates corresponding to a single photo-electron emitted by the first photo-cathode of the image intensifier chain. The cluster width, with respect to the point-like photo-electron, is due to the resolution of the readout chain and is well described by a Gaussian distribution with a sigma of 18 μm in detector space. This value combines the resolution of the readout chain itself and the magnification of 1.7 before the readout. The distortions introduced by the electrostatically focusing image intensifiers are corrected using measurements of a reference grid pattern [6].

For single-prong events (pions and muons) tracks are found by a straight line fit through the cluster barycentres, requiring at least 6 hits within a track road of ±100 μm. For multi-prong events an algorithm has been developed which projects the pulse heights on a circle centered around the vertex, where tracks are defined as the maxima in this distribution [7].

The fitted track is on average 6 mm long and formed by 5.2±0.6 hits per millimetre of projected track length. Compared to perpendicularly crossing single-prong events, the number of hits per projected track-length is higher due to the inclination of tracks coming from multi-prong events.

The track residual distribution exhibits a narrow Gaussian peak with $\sigma = 28$ μm, superimposed on a wider background distribution. The two-track resolution has been determined to $\sigma = 33$ μm.

Noise can be produced by mainly three sources: delta-rays, optical cross-talk between capillaries and backscattering of photo-electrons in the micro-channel-plate image intensifier. The latter one is reduced in the analysis by a pulse height cut. One fraction of noise is related to optical cross-talks in the target due to an insufficient amount of extra-mural absorber. Those noise hits are similar in shape and pulse height to the signal hits.

Short delta-electrons cannot be resolved from particle tracks and, if they appear between the tracks, these hits will be assigned to the closest track. Furthermore, in the vertex region of multi-prong events (see e.g. Fig. 6c), clusters tend to overlap, in particular in very forward showers as seen for example in Fig. 5a.

If the noise-clusters are far away from the track (backscattering up to ≈800 μm, optical cross-talk up to ≈2 mm) they are rejected in the track finding algorithm. Short

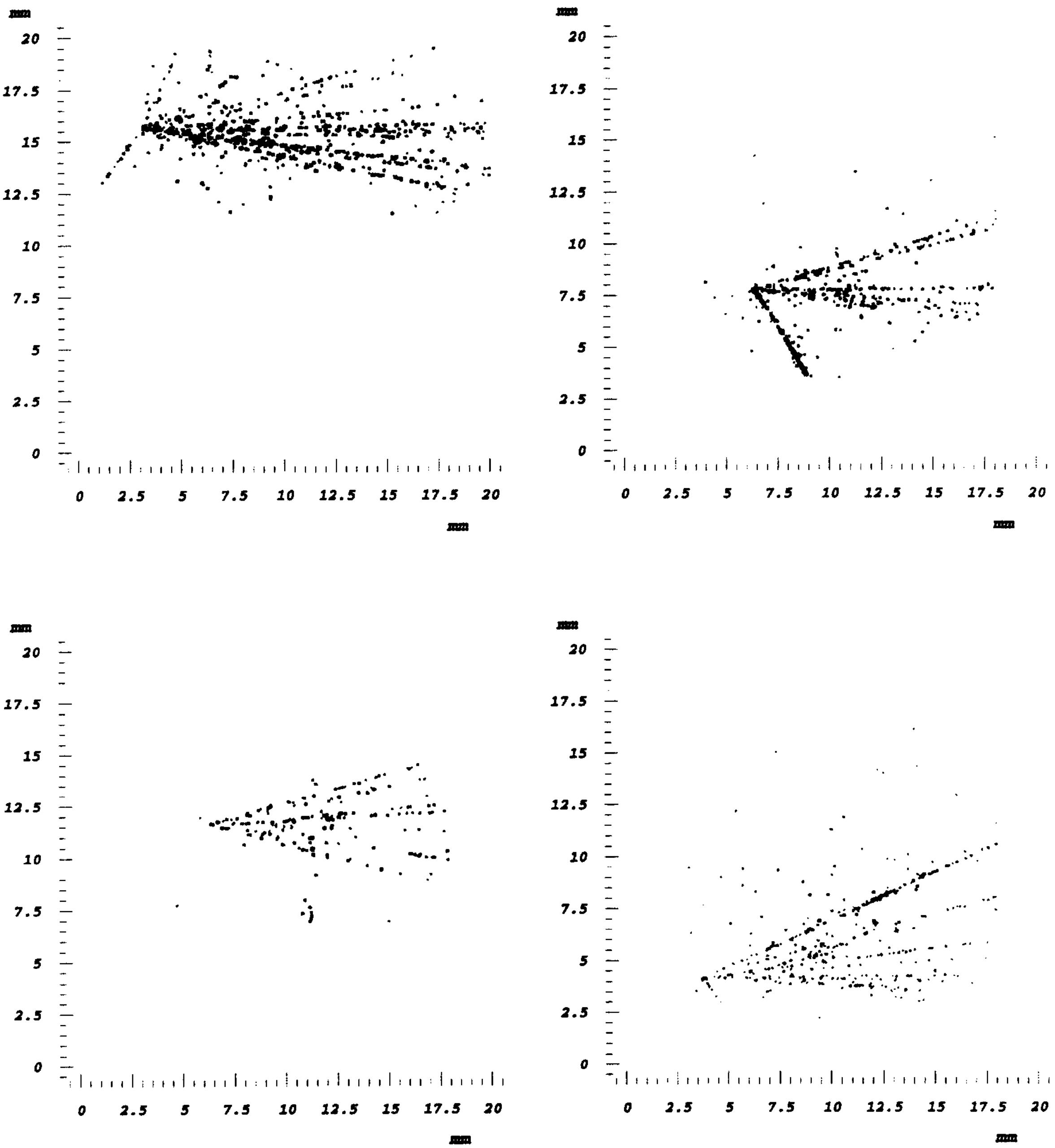


Fig. 5. Neutrino interactions in the large-volume prototype, seen by the Megapixel CCD.

delta-electrons and the short-range parts of backscattering and optical cross-talk are constituting tails in the track residual distribution.

The vertices are uniformely distributed over the target cross-section. From the generally forward direction of the tracks, it is expected that the vertex resolution along the beam direction is worse than along the perpendicular direction. The vertex resolution has been determined to 110^{+310}_{-110} μm in beam direction and 30^{+40}_{-20} μm transverse to the beam direction, where the quoted errors indicate the spread of the distribution.

5. Future prospects

In 1996 the analysis algorithms will be further improved based on more data. Furthermore, the present prototype is now equipped with an upstream passive layer (1 mm thick

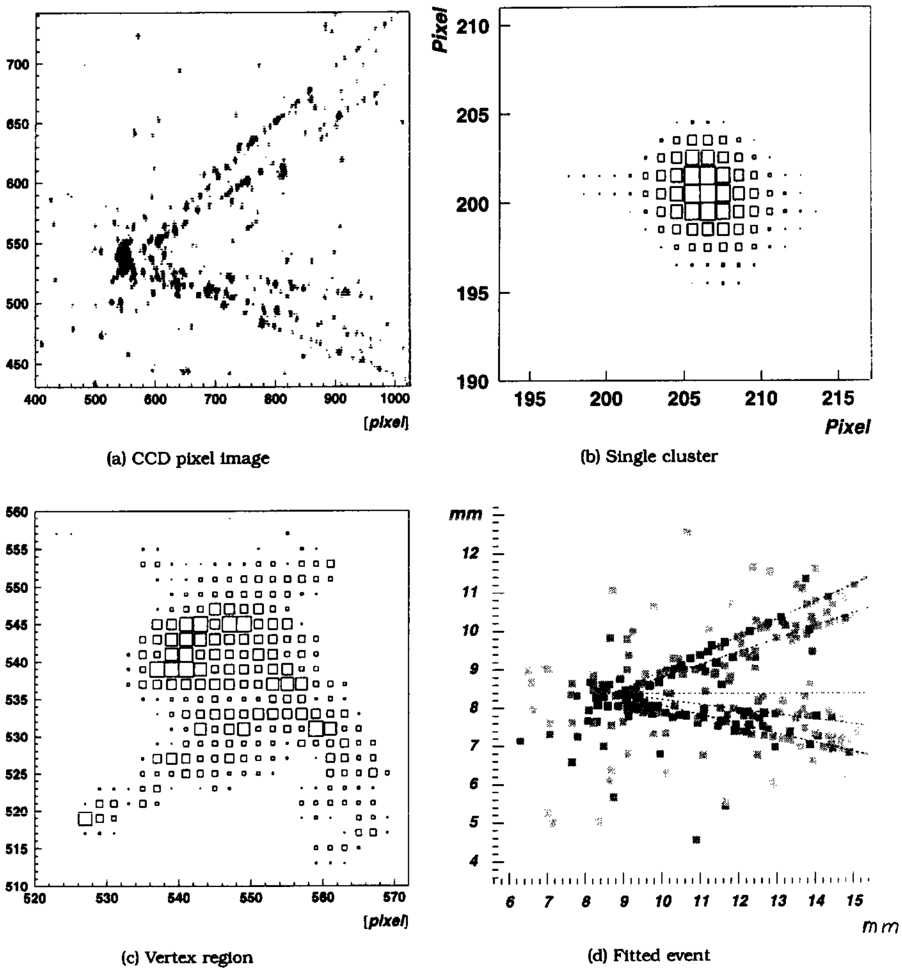


Fig. 6. (a) CCD pixel image of a neutrino interaction, (b) Pixel distribution within a single cluster, (c) Zoom of the vertex region, (d) Fitted tracks and reconstructed vertex.

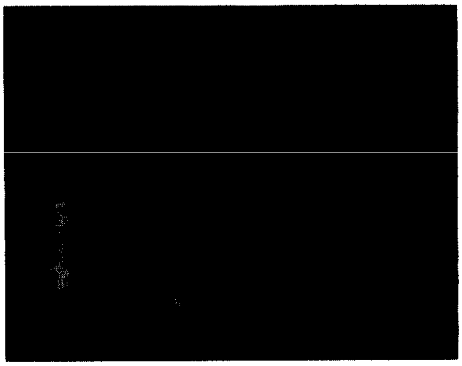
lead plates covering the full target surface of $2 \times 180\,\mathrm{cm}^2$) in order to investigate the reconstruction efficiency for vertices outside the capillary target. Studying the vertex resolution versus the depth in the non-sensitive material will allow us to optimize the design of a layered target, one of the considered options to increase the total target mass for future neutrino experiments.

Further research is also going on in the construction of large-size bundles. Based on the experience gathered with the present prototype the bundle drawing procedure has been improved. The thickness of non-sensitive glass constituting the mutli-walls has been reduced therefore increasing the packing fraction of the bundle and reducing dead spaces. Furthermore the amount of interstitial absorber has been increased. The new prototype has a hexagonal cross-section of 3 cm diameter. It is based on hexagonal multies (as the present prototype) which are fused together.

After tests of this prototype with muons, the target will be installed in the longitudinal orientation with respect to the neutrino beam, allowing a study of the event visualization in both orientations – transverse and longitudinal to the beam. The kink detection efficiency is expected to be higher in the longitudinal orientation, as Monte-Carlo studies show, if the vertex is not overlayed by the forward going hadronic shower. To study the possible problems connected with the overlay of the shower, tests will be done with the target slightly tilted with respect to the beam direction.

To improve the overall resolution of a capillary detector, R&D on the readout components is going on. The resolution of our image intensifier chain is dominated by the poor resolution of the micro-channel plate (MCP) which is typically $\leqslant 25$ lp/mm. If the signal is detected with a conventional CCD, the MCP is needed to achieve the amplification required to detect single photo-electrons

(a) View at the cross-section of a SCHOTT sample.



(b) Zoom into the capillaries.

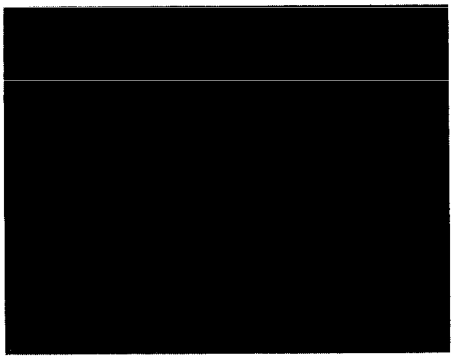


Fig. 7. Microscopic view at the cross-section of a capillary layer; (a) and (b) produced by SCHOTT and (c) produced by Geosphaera.

emerging from the first photocathode of the image intensifier chain. We are developing a new device called Electron Bombarded CCD (EBCCD) providing a higher resolution and more compact readout chains. After successful tests of various prototypes [10,17] the readout chain for a new detector will be built with a large EBCCD of 1024×1024 pixels.

Another foreseen application of the capillary technique is a microvertex detector for the LHC-B experiment [18]. A prerequisite to realize the needed configuration is the construction of planar capillary layers (~1 mm thick) with a surface of several square-centimetres. The present trial by Schott [b] is to compose these layers by gluing or fusing together rectangular multies of about 2×10 mm^2 cross-section, while Geospaera [d] is starting from squared multies of 1×1 mm^2 or 2×2 mm^2 cross-section. First components have recently been delivered by both companies. A microscopic view at the cross-section of small layer-components is shown in Fig. 7.

6. Summary

A novel detector based on liquid-core fibre arrays has been developed. For the first time a prototype has been used in a neutrino beam and high quality images of neutrino interactions were recorded and analyzed. The sample of events recorded in the 1995 run allowed us to develop analysis tools and to derive a first estimation of the tracking and vertexing capabilities of such a capillary detector. The statistics will be increased in 1996. Furthermore, data are taken with the target equipped with a passive upstream layer to study the reconstruction efficiency of vertices outside the active target itself.

Within the framework of the CERN RD46 Collaboration, applications of this detector technology for neutrino and beauty physics are under study. Presently, the capillary technique is one of the possible options for a microvertex detector in the LHC-B experiment at the future LHC collider.

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[9] Pilot target group: NIKHEF, Amsterdam, the Netherlands; Humboldt University, Berlin, Germany; IIHE (ULB-VUB) Bruxelles, Belgium; JINR Dubna, Russia; CERN, Switzerland; Université Catholique de Louvain, Belgium; Università "Federico II" and INFN Napoli, Italy; IHEP, Protvino, Russia; Università "La Sapienza" and INFN, Rome, Italy; and Schott Fibre Optics Inc., USA; GEOSPHAERA Research Center Inc., Russia.

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[a] 1MN for 1-Methylnaphthalen as solvent, 3M15 is the scintillating dye, a trademark of Geosphaera, Russia.

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

[c] Megapixel CCD: Thomson TH 7896A, Division Tubes électroniques, Bouloge-Billancourt, France, Readout electronics: Maxvideo200, DataCube, Zurich, Switzerland.

[d] Geospaera Research Center Inc., c/p 6, 117133, Moscow, Russia.