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NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Capillary detectors for high resolution tracking

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We present a new tracking device based on glass capillary bundles or layers filled with highly purified liquid scintillator and read out at one end by means of image intensifiers and CCD devices. A large-volume prototype consisting of 5×10^5 capillaries with a diameter of 20 μm and a length of 180 cm and read out by a megapixel CCD has been tested with muon and neutrino beams at CERN. With this prototype a two track resolution of $33 \mu m$ was achieved with passing through muons. Images of neutrino interactions in a capillary bundle have also been acquired and analysed. Read-out chains based on Electron Bombarded CCD (EBCCD) and image pipeline devices are also investigated. Preliminary results obtained with a capillary bundle read out by an EBCCD are presented.

1. Introduction

Detectors made of plastic scintillating fibres have been successfully operated in several high energy physics experiments both for calorimetry and for tracking. In tracking devices, generally, a huge number of scintillating fibres is packed in bundles or superlayers. Scintillation light is propagated along the fibres to a read-out stage by means of total reflection at the core-cladding interface.

The read-out stage consists of an optoelectronic chain of image intensifier tubes to amplify the light signal and of a photosensitive Charged Coupled Device (CCD) to record the image.

In the past few years, various groups [1–3] have contributed to the development of a new particle detection technique based on the use of glass capillaries filled with liquid scintillator (LS). Our group has been working in this field for several years and has recently achieved remarkable progress both in the production of highly purified li-

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quid scintillators and of capillary bundles and layers. We are presently developing thin planar layers in collaboration with two firms: Schott Fiber Optics and Geosphaera [4,5]. In addition, we are developing new optoelectronic chains containing a gateable Vacuum Image Pipeline (VIP) [6] and an Electron Bombarded CCD (EBCCD) [7]. These new devices improve the spatial and temporal resolution of the detector and permit its use with high event rates.

2. Detector conceptual design

A tracking detector consists of an active part made by several multi-capillary bundles or "multies" (arranged, depending on the experimental requirements, in a bundle or in a series of layers) filled with liquid scintillator, and of a read-out chain composed by a series of image intensifiers (II) and by a CCD device. Light propagates along the capillaries from the production point, where the passing particle has interacted with the scintillator, up to the optoelectronic chain. A large light attenuation length (λ_{att}) is needed to efficiently detect particles hitting the detector far from the read-out device. This implies the use of highly purified liquid scintillators.

2.1. Construction of the capillary bundles

The construction of a "multi" starts from stacks of glass tubes with a diameter of the order of 1–2 mm. In the interstices between the tubes black glass bars are inserted (Extra Mural Absorber or EMA) in order to absorb the light that could propagate outside the tubes. The stack is then heated and drawn in such a way that the length increases and the tube diameter proportionaly decreases to give a multi-capillary bundle. In a second step, several stacks are packed together and undergo the same process to form a bundle with long capillaries with micrometric diameters (Figure 1). This technique is well developed in commercial companies such as Schott and Geosphaera.

The bundles thus obtained are then cut by means of a circular diamond saw and filled with liquid scintillator.

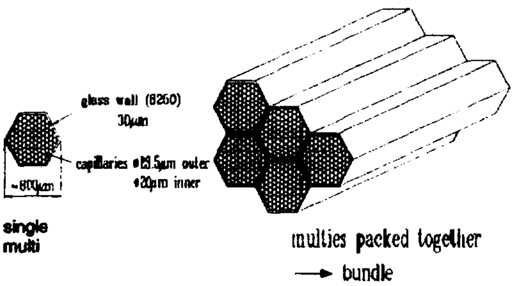

Figure 1. Construction of the "multies"

2.2. The liquid scintillator

Because of the high refractive index of the glass ($n_g = 1.49$) the choice of scintillators is restricted to 1-Methyl-Naphtalene or Iso-Phenyl-Naphtalene based organic solvents, with refractive index $n_{1MN} = 1.62$ and $n_{IPN} = 1.58$ respectively. They have been tested together with newly synthesized dyes. The scintillation efficiency for these scintillators is 20–50% higher than that of conventional plastic scintillators and the trapping efficiency of liquid core fibres is 40% higher than that of standard polystirene-based fibres. With a dye concentration of 3 g/mm, the attenuation length of these liquids, at the ordinary level of purification, is less than 1 m.

We have tested different combinations of the two highly purified liquids and three scintillating dyes measuring λ_{att} in 500 μm diameter capillaries. The measured attenuation lengths (in cm) for different combinations of solvents and dyes are shown in the table below [1].

	R45	3M15	R39
1MN	287	342	186
IPN	165	402	-

For our application we have chosen 1MN with 3 g/mm 3M15, obtaining $\lambda_{att} \sim 400$ cm in a single 500 μm diameter quartz capillary and about 300 cm in a bundle of 20 μm borosilicate

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[1] The names of scintillating dyes are a trademark of Geosphaera

glass capillaries.

The presence of oxygen solved in the liquid is a well known cause of deterioration both in scintillation efficiency and light transmission (see for example [8]). For this reason the bundles are filled under argon atmosphere and the liquid is circulated for several hours.

Detectors based on glass capillaries filled with liquid scintillator are extremely radiation resistants. Studies on the radiation hardness of liquid scintillators have shown for some of the mixtures a very high stability up to doses of 180 *MRad* [9]. Moreover the reflectivity at the liquid-glass interface is almost unaffected by the (even small) radiation damage of the glass.

2.3. The optoelectronic chain

The pattern provided by the capillary array is an image made by a few photons (of the order of one per capillary), so that not only a good quantum efficiency, but also a large light amplification is needed before the image can be read-out by a position sensitive device such as a CCD. The amplification ($10^4 - 10^5$) is provided by an optoelectronic chain of image intensifiers (II). The first element of the chain is an electrostatically focused II with relatively low gain, low noise and good spatial resolution. The core of the whole chain is a Micro Channel Plate (MCP) Image Intensifier. This gateable device provides a high gain ($\sim 10^3 \div 10^4$) at the price of high (exponentially distributed) gain fluctuations. This is coupled to other electrostatic IIs to magnify and demagnify the image in order to compensate for its relatively poor spatial resolution and fit the CCD dimensions. Then the image is sent onto the CCD for the read-out and the acquisition.

A CCD device consists of an image zone composed of $10^5 - 10^6$ light sensitive pixels and a read-out stage consisting of *registers* (figure 2). The pixels from image zone store a charge proportional to the light impinging on them. The charges are parallely transferred line by line to one or two registers, serially read-out from one or both sides. The advantage of such a read-out scheme is that up to 10^6 pixels are read out by the same device with only one or a few output channels. The drawbacks are the very low CCD gain ($\sim 1e^-/\gamma$) and the relatively slow (order of *ms*) serial read-out of CCD registers.

In order to overcome the increase of noise, the poor spatial resolution and the need of more II stages due to the use of MCP image intensifiers we are developing an optoelectronic chain based on Electron Bombarded CCD. This device consists of an electrostatically focused II having a CCD chip at the place of phosphor screen. Electrons coming from the photocathode, are accelerated up to 15 keV, reach the *reversed* CCD chip and create $\sim$ 4000 electron-hole pairs into it (Figure 3).

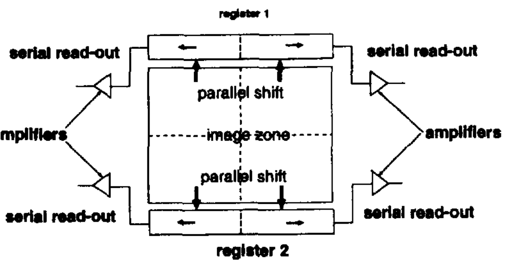

Figure 2. Block schematic of a CCD device

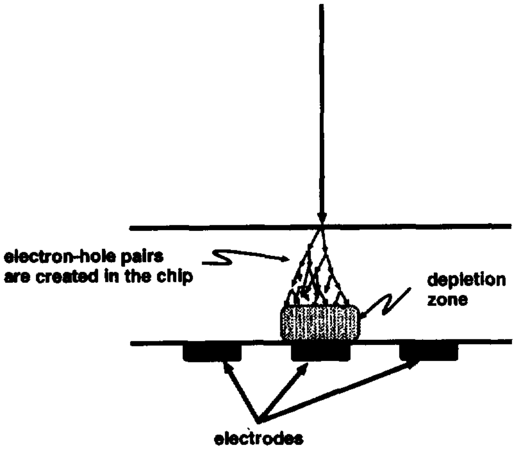

Figure 3. Principles of EBCCD basic operation

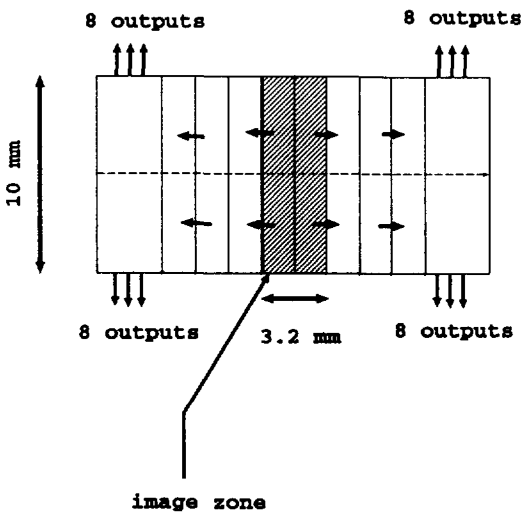

Figure 4. The buffered CCD

In order for the electron-hole pairs to reach the zone of the chip where they are collected by the electrodes, the chip itself is thinned to $\sim 10\ \mu m$, to be compared with the ordinary thickness of $\sim 300\ \mu m$ of the ordinary CCD chips. Compared to the MCP, the EBCCD gain is extremely stable. This high gain device is also gateable by an external trigger, as the MCP; thus it permits to reduce the elements of the optoelectronic chain, eliminating the MCP. This improves the spatial resolution, reduces the noise level and gives a high chain compactness.

Since the CCD read-out is relatively slow, two possible tools have been studied to permit the use of this technique in high rate environments: the buffered CCD (Figure 4) and the Vacuum Image Pipeline tube (VIP) (Figure 5).

In a buffered CCD, pixels from image zone are parallely transferred to a buffer zone of the CCD until a new image is acquired. Then they are transferred to a further buffer zone, and so on until they reach the read-out stage, where they are acquired through several parallel channels in times of the order of 10 μs, or deleted.

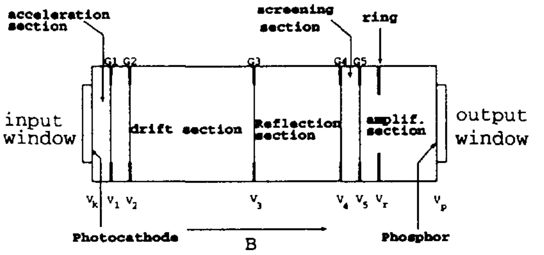

Figure 5. Schematics of the Vacuum Image Pipeline

A VIP is a vacuum tube where electrons coming from a photocathode coherently drift and are reflected back and forth until a trigger signal reaches the proper electrode. When this happens the electrons can either reach a phosphor screen to be acquired as an image or be flushed away. To save the image resolution, the drifting electrons are kept on a circular helic by a longitudinal uniform magnetic field ($\sim 0.1\ T$). This prevents the use of this device in environments where strong magnetic fields are present. The VIP device already exists as a prototype, giving delays up to 1.5 μs with a time resolution of the order of 20 ns and a spatial resolution of the order of 30 lp/mm [6][2]. In future the delay could be increased up to tens of μs.

3. Tests and measurements

An R&D program has been recently approved by CERN to study and develop the applications of capillary detectors (RD46). It follows an R&D *Pilot Project* carried out in the frame of the CHORUS experiment on $\nu_\mu - \nu_\tau$ oscillation at the CERN SPS.

In the framework of the Pilot Project, a $2 \times 2 \times 180\ cm^3$ bundle of 20 μm diameter capillaries is read out by an optoelectronic chain with four electrostatic II, an MCP and a *megapixel* (1024×1024 pixels) conventional CCD. This system has been

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[2] The spatial resolution is given in terms of the maximum density of black-white line pairs (lp) that can be resolved

tested on the neutrino beam, in a location just upstream of the CHORUS apparatus. Muon tracks can also be recorded. With this prototype, for m.i.p. tracks, we have measured a hit density of 3.5 hit/mm at 1 m from read-out[3], a spot size $\sim$ 20 μm, a two track resolution $\sim$ 32 μm and a track residual $\sim$ 25 μm.

We detected neutrino interactions in the capillary target that were observed and reconstructed also by the CHORUS apparatus. One of these interactions and its reconstruction by CHORUS is shown in Figure 6. Using the small sample of neutrino interaction available in the capillary target we measured a vertex resolution of $110\pm^{31}_{10}$ μm in the beam direction and $30\pm^{4}_{2}$ μm in the transverse direction [10].

A second capillary target read out by a chain composed by two IIs and a 532 × 290 pixel EBCCD has been tested upstream the *Pilot* target on the same beamline. This target is going to be tested with a chain composed by only one II and a *megapixel* EBCCD with 1024×1024 $13\mu m^2$ wide pixels. Preliminary results of the analysis of cosmic ray tracks read out with the smaller EBCCD show clean tracks. The RMS noise fluctuation has been measured to be of the order of 5 ADC counts per pixel, while the single photoelectron signal is spread over $\sim$ 10 pixels and corresponds to $\sim 10^3$ ADC counts. Standalone laboratory tests on the megapixel EBCCD coupled to a single electrostatic II have shown clear indications of single photoelectron detection and a signal to noise ratio exceding ten.

4. Possible applications

In high-energy physics this technique is particularly relevant to neutrino experiments, to experiments at high luminosity colliders and to those fixed target experiments, where the detection of short lived particles is crucial.

Studies on possible neutrino experiments at LHC, using targets composed of alternate layers of absorber and capillary bundles are being carried out. A test on the *Pilot* target preceded by a

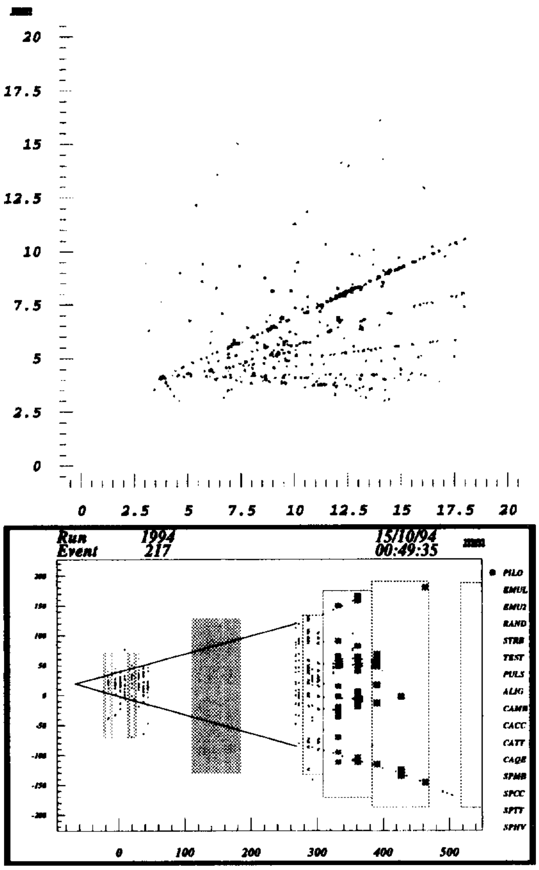

Figure 6. Image of a neutrino interaction in the capillary target placed upstream of the CHORUS apparatus together with its reconstruction by CHORUS.

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[3] We remember that typical hit densities that can be obtained with silicon microstrip telescopes are of the order of less than 1 hit/mm

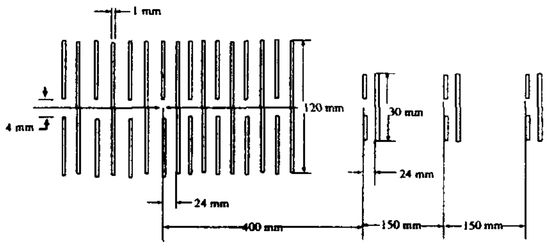

Figure 7. Schematics of the capillary vertex proposed for the LHC-B experiment

thin lead layer is under way, to verify the potentiality of such a configuration.

For what concerns the detection of short lived particles, the LHC-B experiment (a project for a collider experiment on B physics at LHC) is considering the possibility of using a capillary microvertex detector. Figure 7 shows a sketch of this detector as from the LoI [11]. It is composed of 1 *mm* thick capillary layers of 16 μm capillaries, for a total traversed material corresponding to 4% of a radiation length.

Due to the LHC-B foreseen trigger rates, the requirements for the read-out stage of this vertex detector are quite stringent. The read-out technologies presently available give a limitation to the number of channels that is possible to handle. To read the capillary detector described in ref. [11] it is necessary to reduce the number of pixels, increasing their dimensions and thus lowering the detector intrinsic resolution. On this subject an intense R&D work is needed and different strategies are under study. One of the proposed strategies implies the use of a VIP and of a small parallel buffered CCD

5. Conclusions

We have developed a novel particle tracking detector based on liquid scintillator filled glass capillaries. This technique offers several advantages: excellent space resolution (order of 10 μm), high hit density, excellent radiation resistance (order of 100 *MRad*).

The optoelectronic read-out based on CCD devices provides a way to read out a huge number of capillaries with a few electronic channels channels. Signal to noise ratio and read-out compactness can be significantly improved by using EBCCD tubes. Possible pipeline strategies and alternative read-out techniques are one of the subjects of an intense R&D aiming in particular at the use of this technique in an experiment at the future LHC. Further, the R&D efforts on this micro-imaging technique have potential applications in astrophysics, medical diagnosis and possibly other fields.

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