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NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Tracking with capillaries and liquid scintillator

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The technique of glass capillaries filled with liquid scintillator allows the reconstruction of ionizing particle tracks with high spatial resolution. Detectors based on this technique consist of coherent arrays of capillaries having diameters of the order of 20 μm. Light signals are amplified by an optoelectronic chain composed of a series of image intensifiers: the readout is performed through a CCD.

The ongoing research in the field of liquid scintillators has led to excellent results in terms of information density ($\geq$ 5 hits/mm) and radiation resistance (order of 1 MGy). In this paper new results about the effect of ageing and purification of liquid scintillators will be presented.

The RD46 collaboration has developed a completely new detector having a readout chain composed of only one image intensifier followed by a new device: a Megapixel Electron Bombarded CCD. First images of neutrino interactions will be shown, together with preliminary measurements of the resolution of the detector.

1. Introduction

The new glass capillary technique allows to build high resolution tracking detectors. It is an extension of the well known scintillating fibre tracking technique which joins the advantages of glass and plastic fibres.

A detector based on this technique is made of an array of glass capillaries (bundle) filled with liquid scintillator (LS). The section of the bundle is generally square or hexagonal, so that in principle it is possible to build detectors of any shape by stacking many bundles together. The collaboration has experimented bundles having sections up to several cm^2 and lengths on the order of 1 m. More recently the RD46 collaboration at CERN is extending the Research and Development program to the production of thin layers (order of 1 mm thick) of capillaries to be used [1]

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Each capillary acts as a scintillating fibre, the refractive index of the LS (core) being higher than that of the surrounding glass (cladding). Part of the scintillation light produced by incident ionizing particles is trapped by total reflection and reaches the end of the capillaries. The image of a track, as it comes out from the bundle, is composed of few isolated photons. In order to have a detectable signal on a position sensitive device like a CCD, this must be preceeded by an intensification stage having a high quantum efficiency and a gain of 10^5 or more. Such a high gain requires a chain of intensifying elements. A detected photon produced in the bundle appears on the CCD as a group of pixels (spot) with pulse height above the background level.

In the last few years there have been strong technical advances, leading to excellent performances in terms of space resolution (as low as 6 μm [2]) and information density (order of 5 detected hits per mm). Moreover, currently used liquids offer a very low attenuation of the scintillation light with the distance from the readout (attenuation length λ_{att} = 2–4 m), and a decay time constant of several ns [3,4]. Unlike standard polystyrene (PS) fibres, glass capillaries easily allow to insert Extra Mural Absorber (EMA) to avoid that the light which is not trapped in the original fibre could reach the readout and generate optical noise. For some liquids a radiation resistance of $\simeq$ 1 MGy has been measured [5], which is much higher than for plastic fibres with comparable light yield: this makes the technique very promising for use in high radiation level environments like those expected in LHC.

In the following we will describe two different detectors based on this technique. The first detector, here called the "Old Detector", has a conventional optoelectronic chain with a CCD readout, while the second detector, here called the "New Detector", is equipped with a newly developed Electron Bombarded CCD tube (EBCCD). New measurements on the characteristics of the LS are presented, and the technique of capillary filling is reported. Finally we show the first experimental results obtained with the "New Detector", and compare them with those already obtained with the "Old Detector".

2. The "Old Detector"

The "Old Detector" [6,7], which is in operation since three years on the Wide Band Neutrino Beam in the framework of the CHORUS experiment [8] at CERN, has a bundle composed of 5×10^5 capillaries (1.8 m long) whose diameter increases from 20 to 34 μm (the bundle section correspondingly increases from 2×2 to 3.4×3.4 cm^2) in the last 30 cm close to the readout. Such a tapered structure allows to magnify the image improving the spatial resolution without losing light, but introduces some complexity in the manufacturing process. The active volume occupied by the LS is close to 55 % of the total volume.

The optoelectronic chain is composed of 5 elements, the main intensification being provided by a micro-channel plate image intensifier (MCP), which is also the gateable element of the chain. The MCP has a relatively poor resolution ($\approx$ 20 lp/mm) with respect to the other 4 electrostatic image intensifiers (IIs) ($\approx$ 40 lp/mm). This is partly compensated for by feeding the chain with images magnified by the tapered bundle, because the resolution at the target level scales accordingly. The image is recorded by a Megapixel CCD (1024×1024 square pixels, 19.5 μm side) produced by Thomson[1].

3. The "New Detector"

A completely new detector composed of a new bundle coupled to an optoelectronic chain of innovative type has been built. The detector has been exposed in July 1996 to the Wide Band Neutrino Beam at CERN.

The bundle is $\simeq$ 1 m long and has a constant section throughout. It is composed of 1.4×10^6 capillaries (30 μm inner diameter) arranged in hexagonal shape, the side to side distance being 4 cm. It was built by Schott[2] according to a new production technique, in the attempt to have a greater active area and a better uniformity over long distances. The active volume is close to 70 % of the total volume (to be compared with the $\simeq$ 55% of the old prototype), while the coherency of the capillary array must still be studied with a

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[1] THOMSON Composants Militaires et Spatiaux, Division Tubes électroniques, Boulogne-Billancourt, France.

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

systematic analysis. After filling with LS a fibre optic plate (FOP) was glued to one end of the bundle to prevent liquid leakage.

The new optoelectronic chain (figure 1) is composed of only one demagnifying electrostatic II similar to the first element of the chain of the "Old Detector" (quantum efficiency ≈ 20 %, magnification factor 40/25), and a Megapixel EBCCD. The length of the full chain is less than one half that of the previous detector.

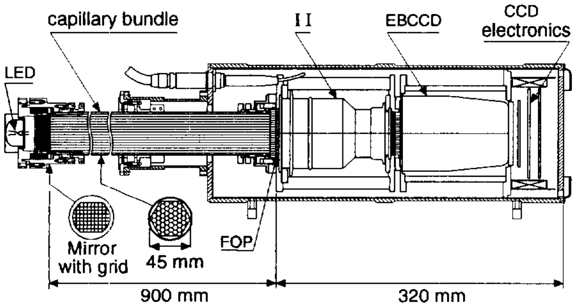

Figure 1. Schematic drawing of the new optoelectronic chain.

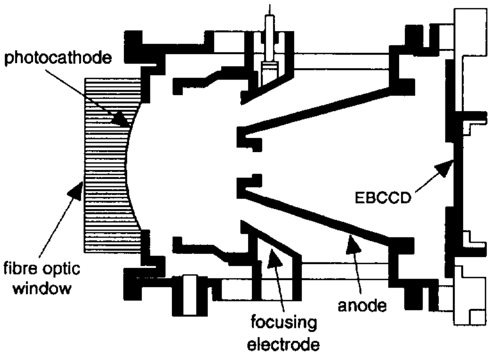

Figure 2. Scheme of the EBCCD.

The Megapixel EBCCD built by Geosphaera (1024×1024 pixels, 13.4×13.4 μm^2 each) has been fully described elsewhere [9]. Here we will only recall its main features. The EBCCD (figure 2) combines the functions of a high gain, gateable II and of a conventional CCD. It works very much like an electrostatic II, but having a reversed, thinned ($\simeq$ 10 μm) CCD in place of the phosphor screen. Electrons produced at the photocathode are accelerated to 15 keV towards the CCD, where they create one electron-hole pair every 3.6 eV of energy released in the silicon. So a very high gain G$\simeq$3000 is obtained, with a fluctuation (σ) which is practically negligeable: $\sigma/G = \sqrt{F/G}$ where F, the Fano factor, is 0.12 for silicon.

This prototype also has a zooming electrode which allows to change continously the magnification of the image from 0.6 to 1.3. In our tests this electrode was set to a voltage giving a magnification of 0.83, so that the overall magnification factor of the chain was equal to 0.53, allowing for a large viewable area of the bundle.

The RD46 collaboration has also developed the low noise control and amplification electronics of the EBCCD. The serial readout is performed through two parallel output registers working at a frequency of 6.5 MHz. The total readout time amounts to 70 ms.

4. The Liquid Scintillator

Several combinations of solvents and dyes have been tested in the last years [4,5].

We are currently using a scintillator based on 1-methylnaphthalene (MN): as for the dyes, the choice is now restricted to two pyrazoline derivatives called[3] 3M15 and R39, both used at a concentration of 3 g/l and having the peak emission at green wavelength. The liquid has a refractive index of 1.62 which, combined with a glass of refractive index 1.49, results in a trapping efficiency of 7.7 %, whereas for standard plastic fibres it is only 6 % [4]. The liquid has a large Stokes shift (e.g. for 3M15 the peaks of the absorption and emission spectra are, respectively, at 360 and 490 nm [10]) and the dye concentration is such to ensure local emission and to have a good compromise between high light yield and low attenuation [11].

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[3] Trademarks from Geosphaera: Geosphaera Research Center, P.B. n. 6, Moscow, 117133, Russian Federation.

A special purification procedure[4] of both the solvent and the dye, strongly increases the scintillation efficiency and decreases the light attenuation [7]. The light yield has been measured with a 500 μm quartz capillary filled with LS when ionization occurred at 10 cm distance from the readout. For the case of 3M15, it turned out [4] to be $\simeq$ 1.5 times higher than in standard plastic fibres after scaling for the trapping efficiencies and for the different sensitivity of the readout system to the emission spectra. For distances from the readout greater than 60 cm the attenuation curve can be reasonably fitted with a single exponential with an attenuation length $\lambda_{\rm att}$ = 3.5 m [7].

The bundle of the "Old Detector" was filled with MN + 3 g/l 3M15 in May 1994 and since then a large number of muon tracks and neutrino interactions have been recorded. Reconstructing muon tracks incident at different distances from the readout and measuring the hit density along the track we can monitor the yield and the attenuation of the scintillation light in capillaries. In figure 3 are shown the results of measurements repeated over two years, with the detector and its readout electronics in unchanged configuration.

At short distances from the readout, no light yield reduction can be observed, neither after two years, while at long distances a reduction is present at the level of our systematic errors.

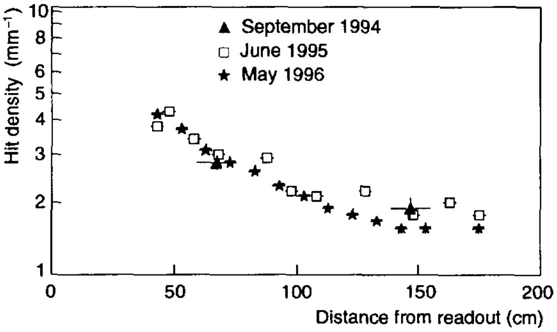

Figure 3. Hit density vs. distance from readout in capillaries. A mirror was placed at the remote end of the bundle.

5. Filling procedure

It is known that the presence of oxygen solved in the LS strongly reduces the light output [12]. We have recently measured the light yield of our LS irradiating a small sample ($\simeq$ 2 cm^3) with a β source under vacuum and under different gas atmospheres [10]: results are shown in figure 4. It can be seen that the light yield increases up to 27 % with respect to that in air when working under vacuum or in atmosphere of noble gases.

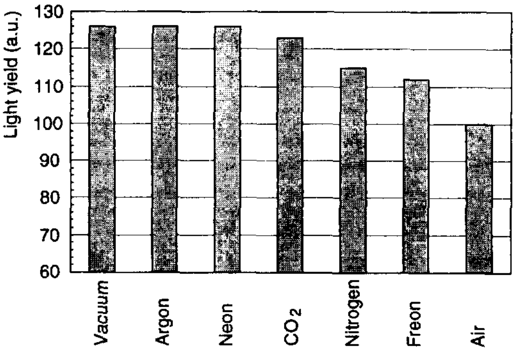

Figure 4. Light yield of the LS under different atmospheres. The light yield in air has been set equal to 100.

In order to avoid any contact of the LS with oxygen or other organic materials we developed the filling set-up shown in figure 5. In this way the liquid comes in touch only with the neutral gas and with glass, teflon and metal: moreover, its quantity for a complete bundle filling is kept to a minimum.

The liquid is first degassed under vacuum, and then the bundle is filled under argon atmosphere. The liquid is circulated for many hours with the help of a peristaltic pump, until the quality of filling is satisfactory. This is checked by illuminating the bundle on one end and looking with a microscope at the other end. If there is any bubble or obstruction somewhere in a capillary, this corresponds to a "black" capillary on the readout end.

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[4] Developed by Geosphaera.

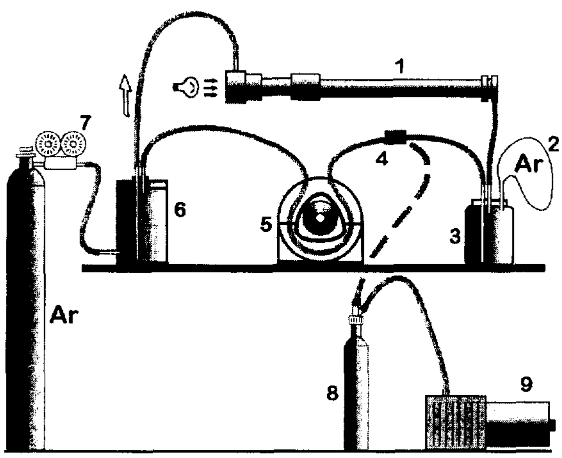

Figure 5. Set-up for filling the bundles: 1. Capillary bundle; 2. Polyethylene balloon; 3. Glass reservoir for LS; 4. Soft hoses for peristaltic pump; 5. Peristaltic pump; 6. Glass vessel; 7. Manometer; 8. Glass vessel for LS degassing; 9. Vacuum pump.

6. Experimental results

In order to measure the performance of the new optoelectronic chain based on the Megapixel EBCCD we analyzed the pulse height profile of isolated (i.e. non coalescent) spots, corresponding to the detection of single photoelectrons. Single photoelectrons are produced by minimum ionizing particles transversally crossing the bundle or by illuminating with a very faint light a grid placed on the input fibre optic window of the chain.

The reconstructed spots have a nearly gaussian pulse height profile, with $\sigma_{sp} = 13$ μm (spot size) at the CCD level, corresponding to 24 μm at the chain input window. This is an improvement with respect to the "Old Detector", for which we measured [7] a spot size of 21 μm at the bundle level which corresponds to 36 μm at the level of the chain input window. This result was obtained by tuning the EBCCD focusing voltage in such a way to reach the same resolution in the X and Y projections. Different tunings have been tested, which optimize the resolution in the Y projection while slightly worsen that in the other projection (figure 6-a). This effect could be due to small misalignments between the axes of the electrodes. We believe that with a more precise mechanical construction the full intrinsic resolution of the chain (which we estimate to be close to 15 μm at the chain input window, figure 6-b) will be attained.

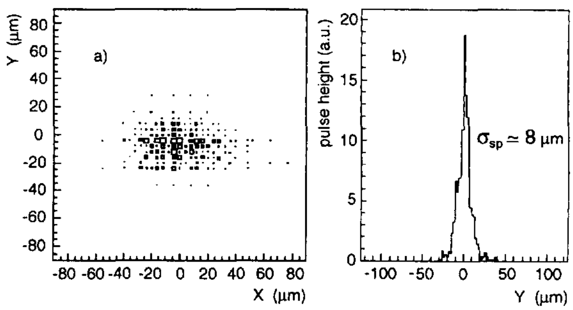

Figure 6. Spot size on CCD for a particular focusing voltage: a) (X,Y) projection; b) Y projection.

Figures 7-a and 7-b show two images of neutrino interactions recorded with the "New Detector" based on the EBCCD: the neutrino beam crosses the detector longitudinally. These images clearly illustrate the performances, in terms of visualization quality and ease of vertex reconstruction, of the technique.

A very preliminary analysis of the track pointing to the lower left corner in figure 7-b has been performed, allowing to estimate the resolution of the detector. The distribution of the track residual (spread of the spots' barycentres around the straight line fitting the track) has a $\sigma_{tr} = 32\mu$m. The capability of the detector to distinguish two close parallel tracks can be estimated using the projection of the total pulse height associated to the track in a direction orthogonal to the fit. For the analysed track the sigma of this distribution (two track resolution) is $\sigma_{tt} = 38\mu$m. Due to the presence of non-gaussian tails in the observed distributions, σ_{tr} and σ_{tt} have been defined as

$\frac{\Gamma}{2\sqrt{2\ln 2}}$, where Γ is the full width half maximum of the corresponding distributions.

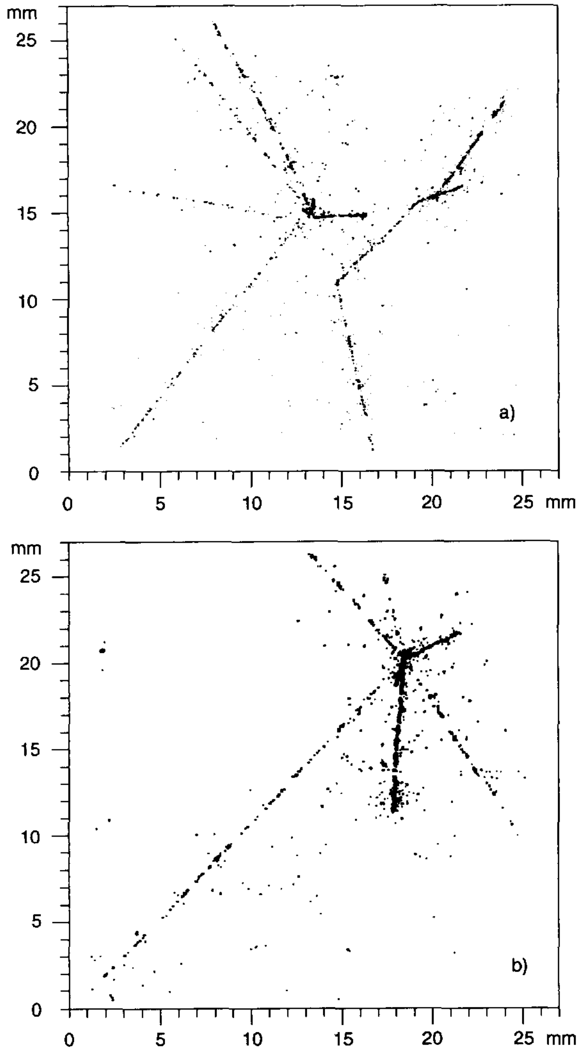

Figure 7. First images of ν interactions taken with the "New Detector". Scales are in mm on target.

Some improvements can be obtained after correcting for the pincushion distortion introduced by the optoelectronic chain. The evaluation of the contribution to resolution from the distortions due to the non perfect uniformity of the bundle throughout its length requires a systematic study of tracks crossing at different positions.

We recall that for the "Old Detector" (having 20 μm inner diameter capillaries) we obtained, after a distortion correction had been performed, a track residual of 48 μm and a two track resolution of 54 μm, where the bundle magnification of 1.7 has been considered.

7. Conclusions

In this paper we report on progresses in the technique of high resolution tracking using glass capillaries and LS.

New measurements of LS performance and technical improvements in the treatment of the LS and in the filling procedure of capillaries have been presented.

Very preliminary results obtained with a detector using a completely innovative readout chain based on an EBCCD have been shown. This new device has better performances in terms of compactness and gain stability and offers a spatial resolution further improving the excellent capabilities of event visualization of this technique.

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