A fast and precise scintillating fiber tracking detector
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Abstract
A scintillating fiber tracking detector has been designed for the UA4-2 experiment. A high optical multiplexing factor allows the reading of hundreds of fibers with a few tens of photomultipliers. The tests of a prototype show that the efficiency after reconstruction is larger than 99% and that the resolution is better than 100μm. This detector could be used close to a high energy high luminosity hadronic collider like LHC, thanks to its high rate capability.

1 Introduction
The experiment UA4 has measured the real part of the elastic amplitude at the SPS collider, at |t| = 0 and √s = 546GeV [1]. The measured value ρ = 0.24 ± 0.04 was found higher than the predicted value of 0.11-0.13 by 3 standard deviations. This astonishing result has lead to a lot of theoretical work and could be the indication of a new phenomenon in very high energy hadronic physics.

The UA4-2 experiment plans to perform a new measurement of ρ with an improved uncertainty. The statistical uncertainty will benefit from the increased luminosity since the commissioning of ACOIL. The systematics will also be improved [2] with new optics giving access to the Coulomb region. The two coordinates of the scattered hadrons will then have to be measured with a precision of 100μm. The charge division chamber which was measuring the transverse coordinate with a precision of 0.5mm [3] will then be replaced by a new detector. The specifications list for this new detector is the following:

- i) a resolution better than 100μm
- ii) insensitivity to the beam peak-up
- iii) a good efficiency down to the bottom of the detector
- iii) resistance to radiation

A scintillating detector fulfills easily the last three requirements. The use of scintillating fibers provides the large segmentation needed for the required resolution.

In the following we present the principle of operation of the detector, its construction, the electronics, the computation of an optimal coding, and the choice of the parameters of the detector. Then the results of the beam test are given.

2 The principle of operation
The detector is made of a few planes (nplanes = 8 in our prototype) of parallel fibers with a diameter of 1mm. The staggering of the planes (figure 1) provides the resolution σ: with a step of 1.2mm, σ = step/(nplane√12) = 40μm.

The fibers are read by photomultipliers (Cf. section 4). As the occupancy in the fibers is very low for an elastic event, they can be grouped on a small number of photomultipliers with a large multiplexing factor. The coding of the fibers onto the PM's is carefully chosen so that the probability that a real track fake a ghost track is minimized (Cf. section 5).

In our prototype, there are 50 fibers per plane, covering an area of (60mm)², and the 400 fibers are multiplexed on 40 photomultipliers. After an amplification, the signal is discriminated either on-line with a discriminator, or off-line after being digitized by an ADC. A fiber is considered as being hit if its photomultiplier is hit. A track is then simply reconstructed as a set of aligned fibers (figure 2).
Figure 1: The staggering of the fibers.

Figure 2: a) the projection on the horizontal plane of the hit fibers related to a given event. The * indicates the location of the drift chamber track. b) the reconstructed track and the associated fibers.

3 The construction of the prototype

We have chosen the Optectron S-101-A fibers for their high number of photons (around 8 photo-electrons per millimeter (γe/mm) after a S20 photocathode). Now-a-days many companies produce scintillating fibers\(^1\). Several samples from various companies are under test.

The fibers were selected on their diameter, cut, polished, and tested with a radioactive source; they were then glued on an aluminium comb. The "V" shape (figure 3) of the comb centers the fibers independently on their diameter with a precision of 7μm.

The planes were then glued together and the bottom of the detector was polished. The detector was then "knitted": each fiber was brought to its photomultiplier; the bundles were glued, cut, and polished. Then the bottom of the detector was aluminized.

4 The electronics

Small diameter — 1/2"— individual photomultipliers were chosen\(^2\) for the absence of cross-talk. The size of the photocathode fits largely the size of a bundle of 10 fibers. A gain of 4.10⁶ at 1000V provides a typical 10mV pulse when a minimum ionizing particle crosses a fiber at right angle. The signal is

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\(^1\)Bicron, Kyowa, Nuclear Enterprises, Optectron, Polivar.

\(^2\)R647 from Hamamatsu
Figure 3: The schema of a comb.

The position of 2 fibers with different diameters is shown.

Further amplified by a factor of 10 by a home made amplifier. Figure 4 shows the spectrum of the signal.

Figure 4: the spectrum of the signal of a photomultiplier reading one fiber. The fiber was exposed to a Sr\(^{90}\) source at a distance of 50cm. The trigger was formed from the signal of a photomultiplier at the other end of the fiber in coincidence with an external scintillator: \(T = F_1 (S_{c_1}, S_{c_2})\).

After calibration with a single photon peak, we find a mean value of 5.1 \(\gamma c\). In the beam test (section 7), the signal was discriminated; in the final experiment, it will be digitized to allow for a more detailed analysis.

5 The computation of an optimal coding

We call coding the assignment of the fibers to their photomultiplier. The map is chosen so that the set of photomultipliers illuminated by a given track do not simulate a ghost track in another part of the detector.

The fibers are numbered: \(f_{i,j}=1, n_f, j=1, n_{plane}\) where \(n_f\) is the number of fibers per plane. We call a couple \(c_i\) the set of \(2 \times n_{plane}\) fibers belonging to the consecutive positions \(i\) and \(i+1\).

For \(i_1 = 1, n_f\) and \(i_2 = 1, n_f\), with \(|i_1 - i_2| > 1\), we compute the number \(n_{i_1,i_2}\) of the common photomultipliers of the couples \(c_{i_1}\) and \(c_{i_2}\). The higher \(n_{i_1,i_2}\), the higher the probability that a track going through the fibers of the couple \(c_{i_1}\) simulates a ghost track in the fibers of the couple \(c_{i_2}\). We

\(^3\)digitized by an ADC LRS 2249A
therefore form the distribution of the $n_{i_1, i_2}$. Let $m$ be the maximum of the $n_{i_1, i_2}$, and $k(m)$ the number of occurrence of $n_{i_1, i_2} = m$ (i.e. the content of the bin $m$). At a given value of $m$, we minimize $k(m)$ by a try-and-error method: we exchange the coding of two fibers; if $k(m)$ is unchanged or becomes smaller we keep the new coding; if $k(m)$ becomes worse we exchange the fibers back.

When $k(m)$ is zero $m$ decreases by one unit, so we also minimize the value of $m$. A stable minimum is rapidly found — in a few million tries. We have shown that this procedure minimizes the probability that a track fakes a ghost track.

6 The choice of the parameters of the detector

The diameter of the fibers was chosen as a compromise between flexibility and efficiency. A diameter of 1mm was chosen providing about 6 γe/mm after a path of 30cm in the fiber. With a step of 1.2mm and a sensitive area of $(60mm)^2$ we have 50 fibers per plane. We now have to choose the number of planes and the number of photomultipliers: the higher $n_{PM}$ and $n_{plane}$, the easier the separation of the track from the ghosts. This was studied with a MonteCarlo simulation.

![Figure 5: The number of reconstructed tracks as a function of $n_{PM}$.](image)

The number of planes of fibers used in the simulation is indicated for each curve.

The number of reconstructed tracks is shown in figure 5 as a function of $n_{PM}$ and $n_{plane}$. Here at least $n_{plane} = 4$ aligned fibers were required to form a track. At high value of $n_{PM}$ (above 40:50) the detector behaves very well: the number of reconstructed tracks is equal to the number of incident tracks. At lower value of $n_{PM}$ the number of ghosts increases. We also see that at a given value of $n_{PM}$ the number of ghosts decreases when $n_{plane}$ increases.

The “coding capacity” clearly increases when the number of planes or the number of photomultipliers increases. The prototype was built with 8 planes of fibers and 40 photomultipliers.

7 The beam tests

The prototype was exposed to a $-70 GeV/c$ pion beam in the X7 beam line at CERN in two three-days runs in June and July 1990. An external measurement of the position of the incoming particle was provided by a UA4 drift chamber [3], and the trigger was formed from a coincidence of counters. An hodoscope made of 6 scintillating fingers with a width of 5mm was placed after the detector.

The spectrum of the number of hit photomultipliers $n_h$ shows a non Poissonian tail (fig 6a) which was not present in a previous cosmic test. The tail is depressed by a factor 5 by the requirement that no more than one finger is hit, so that it is likely to be due to the interaction of the pions in
the detector and/or to multitracks events — the depth of the detector being equivalent to 2% of an interaction length.

![Graphs](image)

Figure 6: a) the distribution of the number $n_A$ of hit photomultipliers. (dashed curve: no cut; solid curve: finger cut (see text)).

b) the distribution of $x_{fiber} - x_{drift}$.

For each event the cut on the number $l$ of aligned hit fibers was applied at the maximum of the histogram of figure 2. It was further asked that $l$ be larger or equal to 2. The efficiency after reconstruction is estimated from the fraction of events having a track in the fiber detector compatible with the track in the drift chamber, and is found equal to 99.4%. The inefficiency is dominated by the contribution from the tail — actually in the $n_A$ peak it is smaller than $10^3$.

An upper bound of the resolution is obtained from the width of the distribution of $x_{fiber} - x_{drift}$ (figure 6b). The resolution of the drift chamber in this test was of the order of 100 $\mu$m, including 70 $\mu$m due to the time jitter of the trigger, so that the resolution of the fiber detector is lower than 100 $\mu$m, whereas the Monte Carlo study predicts 40 $\mu$m for one track events.

8 Conclusion

A scintillating fiber tracking detector has been designed, built and tested for the UA4-2 experiment. It is fast and radiation hard; the ultimate resolution seems to be limited to $20 - 40 \mu$m by the diameter of high efficiency fibers — (200 - 500 $\mu$m). All these features make this detector a particularly convenient tracking detector for an elastic and diffractive experiment close to a high energy high luminosity hadronic collider like LHC.

References