A helical scintillating fiber hodoscope

The EDDA Collaboration: M. Altmeier [a], F. Bauer [b], J. Bisplinghoff [a], T. Bissel [a], R. Bollmann [b], M. Busch [a], K. Büßer [b], T. Colberg [b], L. Demirörs [b], O. Diehl [a], F. Dohrmann [b], H.P. Engelhardt [a], P.D. Eversheim [a], O. Felden [c], R. Gebel [c], M. Glende [a], J. Greiff [b], A. Groß [b], R. Groß-Hardt [a], F. Hinterberger [a], R. Jahn [a], M. Jeske [a], E. Jonas [b], H. Krause [b], U. Lahr [a], R. Langkau [b], T. Lindemann [b], J. Lindlein [b], R. Maier [c], R. Maschuw [a], T. Mayer-Kuckuck [a], A. Meinerzhagen [a], O. Nähle [a], M. Pfuff [b], D. Prasuhn [c], H. Rohdjeß [a], D. Rosendaal [a], P. von Rossen [b], B. Sanz [b], N. Schirm [b], M. Schulz-Rojahn [a], V. Schwarz [a], W. Scobel [b], S. Thomas [a], H. J. Trelle [a], E. Weise [a], A. Wellinghausen [b], W. Wiedmann [a], K. Woller [b], R. Ziegler [a]

[a] *Inst. f. Strahlen- und Kernphysik, Univ. Bonn, Nußallee 14-16, D-53115 Bonn*

[b] *I. Institut für Experimentalphysik, Luruper Chaussee 149, D-22761 Hamburg*

[c] *Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich*

Abstract

A novel scintillating fiber hodoscope in helically cylindric geometry has been developed for detection of low multiplicity events of fast protons and other light charged particles in the internal target experiment EDDA at the Cooler Synchrotron COSY. The hodoscope consists of 640 scintillating fibers (2.5 mm diameter), arranged in four layers surrounding the COSY beam pipe. The fibers are helically wound in opposing directions and read out individually using 16-channel photomultipliers connected to a modified commercial encoding system. The detector covers an angular range of $9^\circ \leq \Theta \leq 72^\circ$ and $0^\circ \leq \varphi \leq 360^\circ$ in the lab frame. The detector length is 590 mm, the inner diameter 161 mm. Geometry and granularity of the hodoscope afford a position resolution of about 1.3 mm. The detector design took into consideration a maximum of reliability and a minimum of maintenance. An LED array may be used for monitoring purposes.

Key words: scintillating fibers, hodoscope, vertex detector, multichannel photomultipliers

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1 Introduction

The availability of cooler rings affords the use of inherently thin targets, such as a polarized atomic beam target, at reasonable luminosities ($\approx 10^{28}$ cm^{-2}s^{-1}), as the internal beam offers effective beam currents 6-7 orders of magnitude higher than the extracted (external) beam. However, employing the internal beam comes at the price that detector access is possible only when the accelerator is out of operation, i.e. hardly ever. Consequently, detectors serving internal target experiments must require only minimal -if any- maintenance, off-line calibration etc.. The purpose of this paper is to describe a cylindric scintillating fiber hodoscope designed with very limited detector access in mind. It was developed for a specific experiment (called EDDA) and is described in this context, but the concept may be adapted to a variety of other applications.

The EDDA experiment [1,2] uses the proton beam provided by the cooler synchrotron COSY [4], and it is designed to provide a high precision measurement of the proton-proton elastic scattering excitation functions ranging from 0.25 to 2.5 GeV of laboratory kinetic energy. Using an internal target, data taking proceeds during the synchrotron acceleration ramp, so that a complete excitation function is measured during each acceleration ramp. Statistical accuracy is obtained by averaging over many cycles (multi-pass technique). The detector concept is based on a fast triggering of coplanar two-prong events of charged particles that fulfill the kinematic correlation between the laboratory angles Θ_1 and Θ_2 for proton–proton elastic scattering (see Eqs. 1, 2 and Fig. 1). The EDDA detector consists of two cylindrical detector shells.

The outer detector shell, consisting of scintillating bars and rings [5–7], was used to take unpolarized differential cross section data with a CH_2 fiber target [1]. Measuring spin observables, however, requires a polarized COSY beam and a polarized atomic beam target. The target beam [3] is about 1 cm in diameter, i.e. large compared to both the COSY beam and the detector position resolution, so that vertex reconstruction requires a second ("inner") detector shell. The latter is the subject of this paper. Measuring spin observables mandates a detector sensitive to asymmetries as a function of polar angle Θ and azimuthal angle φ. A helical detector structure is of obvious advantage in this respect, as it yields continuous coverage in Θ and φ. Therefore, the inner detector shell of the EDDA experiment is a cylindrical hodoscope consisting of four layers of 2.5 mm diameter plastic scintillating fibers which are helically wound in opposing directions so that a coincidence of hits in the lefthanded and righthanded helices gives the point at which the ejectile traversed the hodoscope. It is called a *helical fiber detector* hereafter. Its purpose within EDDA is

- vertex reconstruction of elastic proton–proton scattering events in conjunc-

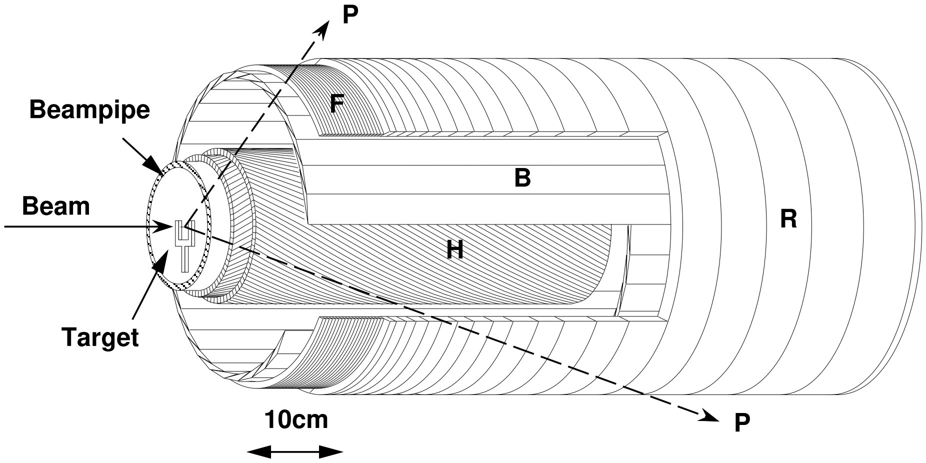

Fig. 1. Scheme of the EDDA detector: Internal COSY beam, phase 1 CH_2 fiber target holder (phase 2: Polarized Atomic Hydrogen Beam Target), beampipe (160 mm diameter, 2 mm thick Aluminum tube), inner detector shell (helical fiber array) with scintillating fibers H (only two of four layers are shown), outer detector shell with scintillator bars B, scintillator semirings R and semi-rings from scintillating fibers F.

tion with the outer shell, thereby
- background suppression of scattering events from the target beam halo and
- improved angular resolution.

In general, however, a helical fiber detector may be used in whatever context a cylindrical hodoscope is needed, restrictions arising only from the number of affordable channels and the light attenuation length of available fibers. The helical fiber detector combines millimeter size position resolution with easy operation, and it requires very little -if any- maintenance.

The paper is organized as follows: In Section 2, we present the geometrical design of the helical fiber detector. In Section 3, selection and preparation of the scintillating fibers is described, while Section 4 is devoted to the multi-channel photomultipliers and PMT bases. In Section 5, we sketch the readout and electronics. The results of test measurements and first applications are presented in Section 6 and conclusions are summarized in Section 7.

2 Detector geometry

The EDDA detector (see Fig. 1). was designed for large center-of-mass solid angle coverage (about 85 % of 4π) of elastic proton – proton scattering events. It provides a fast and efficient trigger on low multiplicity events of a given kinematic signature. Elastic proton – proton scattering events are identified by coplanarity with the beam axis

$$|\varphi_1 - \varphi_2| = 180^\circ \tag{1}$$

and kinematic correlation

$$\tan\Theta_1 \tan\Theta_2 = \frac{2m_\mathrm{p}}{2m_\mathrm{p} + T_\mathrm{p}}. \tag{2}$$

The EDDA detector consists of two cylindrical shells. The outer detector shell covering laboratory angles from 10° to 72° is composed of 32 overlapping scintillator bars (B in Fig. 1) parallel to the beam axis and 29 pairs of scintillator semi-rings (R). Their cross sections have been designed so that ejectiles to be detected deposit a sufficient amount of energy for a highly efficient detection in two adjacent bars and two adjacent semirings. Analysis of the fractional light output is then used [5] to determine the point of incidence by a factor of 5 more accurately than possible on the basis of detector granularity alone. For $\Theta_\mathrm{lab} > 52$ °, the angle resolution is obtained using semirings from square scintillating fibers (2×2 mm^2) and Hamamatsu R4760 multichannel photomultiplier readout [7]. The outer shell length is about 1 m, the inner diameter 320 mm and the outer diameter 388 mm. A detailed description of the outer detector shell can be found in [5].

The inner detector shell -subject of this paper- is about 590 mm long, about 184 mm in outer diameter and 162 mm in inner diameter. It consists of 640 scintillating fibers helically wound and arranged in four layers, two righthanded and two lefthanded with 160 fibers each and closely fitting into one another. The fibers spiral around the beam pipe at a spatial inclination angle of $\alpha = +25.17°$ or $-25.17°$, with respect to the beam axis. Each fiber covers a range of 170° in azimuthal angle φ, so that no ambiguities arise in either φ or the polar angle Θ for events with no more than two particles in the exit channel, i.e. events coplanar with the beam. For higher multiplicities additional information gathered by the outer detector shell is needed to remove combinatorial ambiguities.

The helical detector geometry is such that photomultipliers for the readout can be located either at forward angles (downbeam) or backward angles (upbeam) from the target point. In order to avoid the high background arising from charged particles emitted at forward angles (downbeam), we decided to locate the photomultipliers upbeam. Therefore, the fibers had to be bent to rather small radii in the region of the target access pipes.

Fibers of circular cross section (diameter 2.5 mm) were chosen for reasons given below. Ejectiles, which traverse a layer at or near a point where adjacent fibers touch each other, may produce insufficient amounts of light in either fiber and remain undetected. To have continuous detection efficiency, such "gaps" must be covered by another, like-handed and somewhat displaced helix layer. The four layers are, therefore, arranged into two doublets, each doublet consisting of two coaxial like-handed layers. Within each doublet, the two like-handed layers are rotated against one another in φ by $360°/320 = 1.125°$. Obviously the fibers have to be positioned precisely and reliably (better than ≈ 0.1 mm). In order to obtain such geometrical accuracy and rigidity, the fibers are suspended by four thin (1 mm) support tubes made of Carbon fiber composite material (CFCM) manufactured by STESALIT AG [1]. To ensure precise fiber positioning relative to the support tubes, 160 equidistant trapezoidal guiding grooves of 0.5 mm depth were mill-cut into the outer surface of each tube, and the fibers glued into these grooves. The support tubes are (downbeam) about 50 mm longer than the fiber layers in order to provide space for dowel pins, aligning the tubes/layers longitudinally and azimuthally relative to each other and relative to the beam pipe. Concentric alignment in the radial degree of freedom is ensured by close fitting. We estimate that *each and any* segment of *each and every* fiber is within its nominal position to better than 0.1 mm.

3 Selection and preparation of scintillating fibers

The choice of scintillating fibers with respect to supplier and cross sectional dimensions necessarily is a compromise. Detector granularity (i.e. spatial resolution) must be balanced against the number of affordable fiber channels. Additional requirements may result from the detector geometry, such as easy bending or convenience of mass production. In practice, however, light output is by far the most important criterion. Any deficiency in this respect tends to

- restrict detector geometry, e.g. regarding fiber length
- reduce detection efficiency
- compromise time resolution.

As a rule of thumb, particles to be detected must produce a minimum of about ten photoelectrons, whereever they hit the fiducial fiber volume. The helical fiber detector developed for EDDA requires bending the fibers elastically into helical shape (bending radii ≥ 453 mm), and thermoplastically (see Fig. 2) around target access pipes (bending radii ≥ 5 mm). Both types of bending processes are associated with some loss of scintillation light, so that fiber light output was all the more important in fiber selection. Various round and sqare scintillating fibers were tested in the course of this work. Square fibers were not found useful, since core and cladding are too easily damaged in the process of bending. The highest light output, as of fall 1995, was obtained

[1] STESALIT AG Kunststoffwerk, CH-4234 Zullwil/SO, Switzerland

with scintillating fibers of the type SCSF-81 NC, made by Kuraray Co.[2].

Round SCSF-81 NC type fibers were chosen for the helical fiber detector described here, and a diameter of 2.5 mm was found to suit the EDDA geometry. The fiber core consists of polystyrene (n_{core}=1.59) doped with dyes, the peak emission wavelength being 437 nm (blue light). The core is surrounded by 75 μm thick cladding made of fluorinated polymethylmethacrylate (FPMMA) [8]. The refractive index of this cladding is 1.42, a substantial improvement over the "standard" of about 1.49 (PMMA) and boosting the high trapping efficiency from 3.4 % to 5.3 %.

The cladding is surrounded by an extra mural absober (EMA) providing protection against optical cross talk as well as mechanical damage. We used Bicron Reflective Coating BC-620 as EMA, a "white paint" especially developed for coating scintillating fibers. A homogeneous coating was obtained by immersing each fiber vertically into a cylindrical container filled with a solution of one part of water and two parts of liquid BC-620. Each fiber was immersed two to three times.

The attenuation length obtained with the fibers chosen was measured to be -not counting light losses due to bending- (230 ± 10) cm, which substantially exceeds the required fiducial length of about 50 cm and the total fiber length of about 130 cm. No light guides were needed to connect fiducial fiber length to PMT's, neither in terms of light loss due to scintillating fiber length "misused as clear fiber", nor in terms of background ejectile count rate, because the relevant fiber length is at backward scattering angles up-beam of the target.

The structure of the helical fiber detector requires bending the fibers into helix shape at a 50 cm scale. This bending achieved by elastic deformation of the fibers and the corresponding light loss is slight. The fibers were fixed to the grooves of the CFCM support tubes using a two-step process: First, some drops of cyanacrylate glue were used for temporary fixing them provisionally in few seconds. Then, a solvent-free epoxy glue (Ciba-Geigy XW 485-3 / XW 1115) was used to fix the fibers to the CFCM tubes at full length. The EMA coating prevents detereoration of the fibers caused by glue.

In the region of four target access pipes, the fibers had to be bent to rather small radii (between 1 and 3 cm, see Fig. 2). This bending was achieved using thermoplastic bending. To avoid deterioration of the scintillating properties the bending of fibers must take place under well-controlled conditions. Best results were obtained using a stream of hot air heating the scintillating fiber locally to a temperature of $(103\pm1)^{\circ}$C. This temperature corresponds to the so-called glass transition temperature of polystyrene [9]. Due to their mechan-

[2] Kuraray Co., Ltd., Shuwa Higashi-Yaesu Building, 9-1, Hatchobori 2-Chome, Chuo-ku, Tokyo 104, Japan

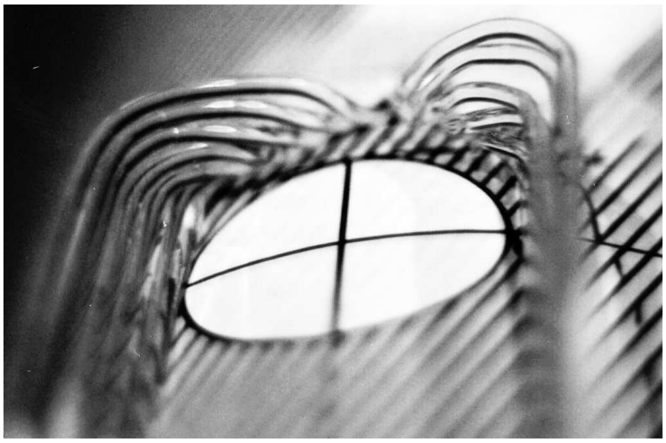

Fig. 2. Form of a fiber bundle in the target area (looking downbeam). The white circle in the center marks size and position of a target access pipe.

ical stiffness, severe bending of the fibers below this temperature causes a noticable reduction of the light transmission due to microscopic cracks in core and cladding. Slightly above the glass transition temperature, light transmission decreases with rapidly increasing distortions of the light guiding cylindrical geometry. Above 110° C, the fiber material melts uncontrollably. Staying within ±1° C of the glass transition temperature, however, affects thermoplastic bending at 5 mm radius and about 25° by less than 30 % light loss. Fibers bent as severely as shown in Fig. 2 suffer light losses up to 50 %. In the few centimeters of such severe bending, no EMA coating was applied, as total reflection between cladding and air was found to improve light transport efficiency, and without inducing noticeable cross talk.

4 Photomultipliers

The helical fiber detector is - as any scintillating fiber detector - built for high granularity. This excludes the use of conventional single channel photomultipliers ("PMTs"), both in terms of cost effectiveness and space requirements. Therefore, PMTs must be used, which provide at least 16 independent channels in one tube. Three different types are commercially available,

- the *multi anode* type, which uses a grid-like dynode structure common to all channels with only the anode segmented into pixels;
- the *multi dynode* type, in which each channel has its own separate dynode structure with only the vacuum tube, the photo cathode and the HV supply in common;
- the *multi channel* type, in which each channel additionally has its own separate photocathode and glass window.

Apart from reasonable quantum efficiency ($\geq 15\%$) and gain ($\approx 10^7$), a multichannel PMT should exhibit, within each tube,

- very little (≤ 2 %) channel-to-channel crosstalk, and
- a rather uniform (within $\approx 30\%$) channel gain.

Deficiencies in these respects carry the penalty of multiplying the effort necessary in signal preamplification, discrimination and readout. Even worse, they may spoil a reliable, efficient and unambiguous detector response and its inherent time resolution (if required). Such deficiencies can be both of optical and electronic nature.

Both crosstalk and variance of channel gain will result, if the scintillating fiber light is not directed at the "right spots" of the photocathode, as defined by the dynode structure (optical deficiencies). Obviously important and dependent upon the fiber diameter and type employed are spot size and spacing, optical coupling, distance between fiber and photocathode (caused by thickness of cathode window and -if used- silicone coupling pads) and alignment with respect to one another. Such problems are much reduced in a multi channel type PMT such as the Hamamatsu R4760.

The Crosstalk was found to be minimal ($\leq 0.5\%$) in the multi channel PMT model Hamamatsu R4760, much smaller than in the multi anode models tested (Philips XP4702, Philips XP4722 and Hamamatsu H4140). This made the R4760 the obvious choice for the helical fiber detector described here. Meanwhile, however, a multi dynode type PMT (Hamamatsu H6568 or R5900) was developed and found to yield comparable qualities [11].

The Hamamatsu R4760 PMT has 16 channels. Its quantum efficiency is $\geq$ 15 % and its maximum spectral sensitivity is near 420 nm, rather close to the emission maximum of the Kuraray SCSF-81 NC scintillating fibers chosen (437 nm). The 16 separate cathode windows are made of boron silicate glass (8 mm in diameter, 2 mm thick), and are embedded in a metal front plate, well suited for coupling the 2.5 mm scintillating fibers employed (see figure 3).

The light coupling between the scintillating fibers and the photomultiplier cathodes was achieved using highly transparent silicon pads of 8 mm diameter and 2 mm thickness. The silicon pads were fabricated according to the following recipe: General Electrics Silicone RTV 615A is mixed with the hardener RTV 615B in a mixing ratio of 30 : 1. After eliminating gas inclusions from the RTV 615A / RTV 615B mixture in a vacuum chamber, the mixture is filled into a special vessel. The bottom of this vessel consists of optical glass to ensure a perfectly smooth surface of the silicone film. To eliminate small air inclusions which occur pouring the silicone into the vessel the hardening procedure takes place in a vacuum chamber at 50°C over 24 hours. Finally, the round silicon pads are punched out of the silicone film.

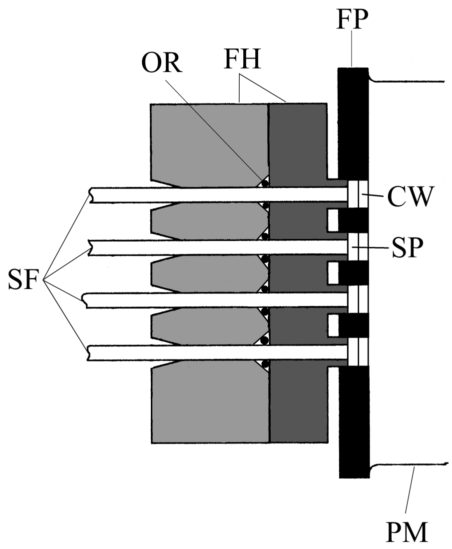

Fig. 3. Cross section of the fiber holding mechanism. CW: cathode window, FH: fiber holder, FP: photomultiplier frontplate, OR: O-ring, PM: photomultiplier housing, SF: scintillating fibers, SP: silicone pad

Since EDDA is an internal target experiment assembly and maintenance of the detector can only be carried out in non-operative periods of the accelerator ring. So it was necessary to develop a system allowing to connect the fibers to the photomultipliers in a plug–and–socket system. The cathode windows of the Hamamatsu R4760 multianode photomultiplier are arranged in a 4×4 matrix on the bottom of 16 pits in the photomultipliers front plate. [3] Each pit has a diameter of 8 mm and a depth of 3.5 mm. The silicone pads are sized to fit exactly into these pits leaving 1.5 mm of pit depth necessary to center the scintillating fibers on the cathode windows. The scintillating fibers are arranged in 4×4 matrix fiber holders made of plastic material fitting the 4×4 matrix of the PM pits (see figure 3). Each fiber holder has 16 bores of 2.6 mm diameter. A simple mechanism using O-rings reliably fixes the fibers to their position. The fiber ends were cut and polished to achieve a high-quality optical surface. The plugs also contain a four spring mechanism to press the fibers homogeneously against the silicone pads of the cathode windows.

The PMT base used is shown in Figs. 4 and 5. It follows recommendations by Hamamatsu to a large extent and emerged as a result of extensive tests with attention to gain stability over a wide range of signal amplitudes and rates. Unlike other photomultipliers the Hamamatsu R4760 does not offer a plug–on base connector. Instead the base assembly has to be soldered onto 28 wires (0.7 mm diameter) reaching out of the rear side of the photomultiplier. Figure 5 shows the circuit board design developed for the R4760 base assembly. The

[3] Originally the R4760 was designed for medical purposes; in the original application micro-titer-plates are placed in the pits to measure luminescence light.

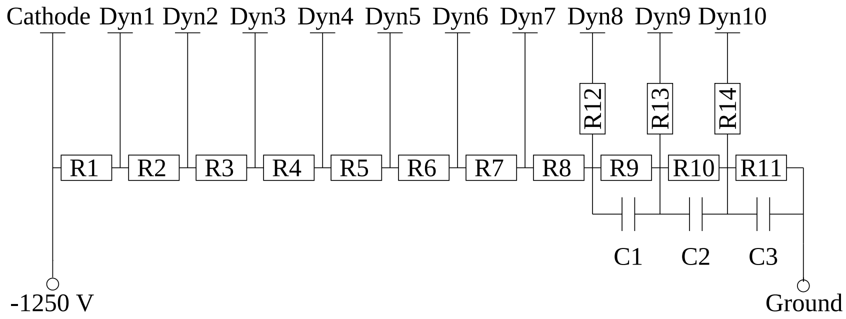

Fig. 4. Circuit diagram of the voltage divider for the Hamamatsu R4760. Resistor and capacitor values: R1, R11 = 110 kΩ, R2, R4 – R9 = 56 kΩ, R3 = 68 kΩ, R10 = 160 kΩ, R12 - R14 = 51 Ω, C1 – C3 = 47 nF.

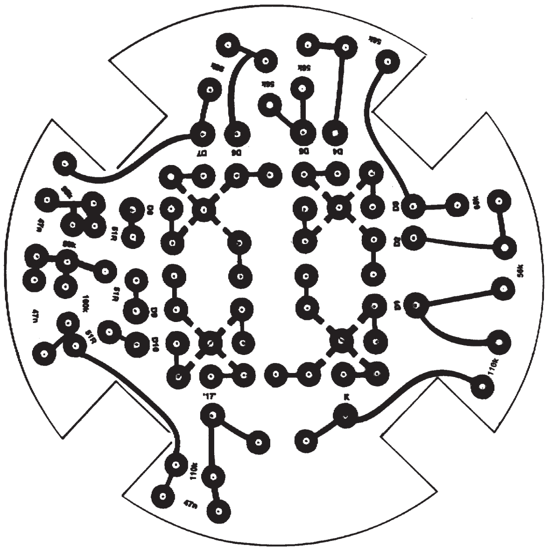

Fig. 5. Circuit board layout of the R4760 base assembly seen from the soldering side. The soldering pads to connect the base assembly to the photomultipliers connection wires are on the opposite side of the circuit board

circuit board consists of a 4×4 matrix for the anode contacts in the center surrounded by the cathode and dynode circuit. To reduce electric shock hazard in case of photomultiplier malfunction each anode is connected to ground using a 10 kΩ SMD resistor. The voltage divider circuits were assembled using conventional resistors and capacitors.

5 Readout

A typical hit pattern in the helical fiber detector as employed in the EDDA experiment involves about 10 of the 640 detector channels. Therefore, data compression at the level of the readout electronics is necessary in order to reduce the amount of data to be processed by the data aquisition system. The

LeCroy Proportional Chamber Operation System PCOS III is a commercially available system providing a data compression needed by the EDDA experiment. It records only the numbers of those channels that have a hit. The PCOS III system has proven reliable and stable in operation with the notable exception of some problems with the cable connectors of the PCOS discriminator cards "2735 PC" and the receiver modules. The mechanical reliability of these connectors is rather poor due to the absence of strain-reliefs and lockings.
The readout configuration is shown in Fig. 6. In order to ensure uniformity of signal amplitudes at the PCOS discriminator inputs (as resulting from variations in PMT channel gains, fiber light output and transmission as well as PCOS preamplifier properties), each channel was fitted to the analogue input of the PCOS III system using an idividual attenuator.

6 Test measurements

Upon delivery, all photomultipliers were tested to assure that quantum efficiency and gain factor of all channels were sufficient. The technical properties of every single photomultiplier channel were recorded in order to assign PMT channels to individual fibers for uniform signal output. The scintillating fibers were tested using minimum ionizing electrons of a ^{90}Sr source. Strong fiber bending near the target access pipes causes larger light losses than the weak bending of the fibers beween the target access pipes. So only the best fibers were used for strong bending to assure a homogeneous light output of all fibers prior to detector assembly.

After thermoplastic deformation and EMA-coating the fibers were tested again using the ^{90}Sr source. Fibers with insufficient light output were replaced. Again, when a whole layer of 160 fibers was completely assembled, it was tested using a ^{90}Sr source rotating around the detector. Pulse height spectra of all detector channels were recorded, and the assignment of photomultiplier channels to fibers was optimized in order to increase detector homogeneity. To allow detector tests in non-operating periods (including assembly and transport) a monitor system was developed. The forward angle end of every fiber is connected to a light guide (0.5 mm diameter, non-doped PMMA fiber with cladding). Bundles of 16 light guides are routed on a light emitting diode (LED). Using pulse amplifiers (FWHM signal risetime $\approx$ 2 ns, signal amplitude $\approx$ 60 V) standard green LEDs produce light pulses with amplitudes and duration like scintillator signals. Using this monitor system, the light transmission of every scintillating fiber, the coupling of fibers to PMTs and the operation of the photomultipliers can be monitored. The receiver modules of the LeCroy PCOS III offer computer controlled output channels. As shown in

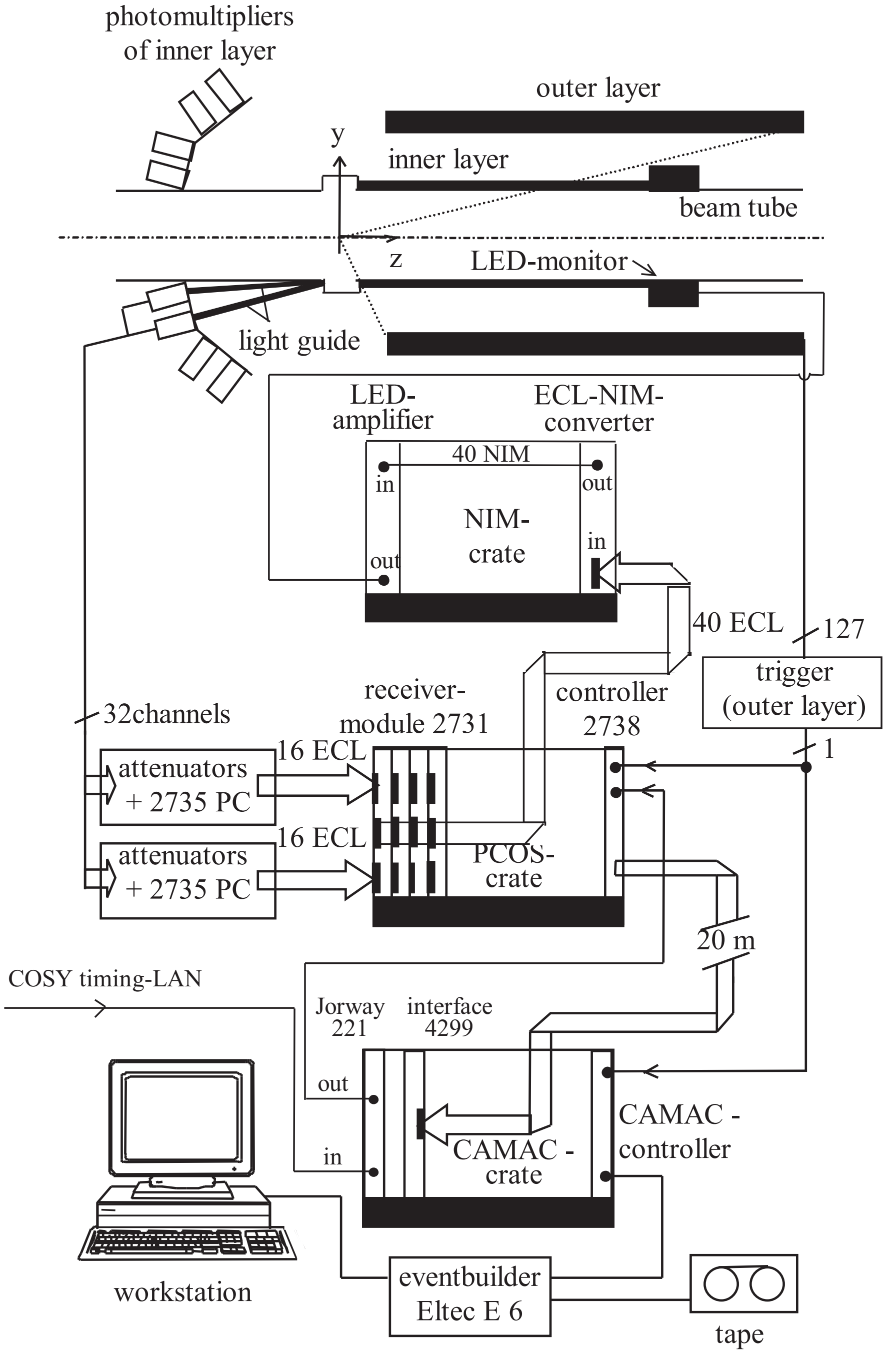

Fig. 6. LeCroy PCOS III front end electronics and LED monitor system of the EDDA detector

figure 6 these output channels can be used to control the LED monitor.

Before and after the transport of the detector to the COSY accelerator facility the complete detector was tested using the LED monitor system to detect any damage caused by the transport, but none was found. After installation as the inner shell of the EDDA detector at COSY, the helical fiber array

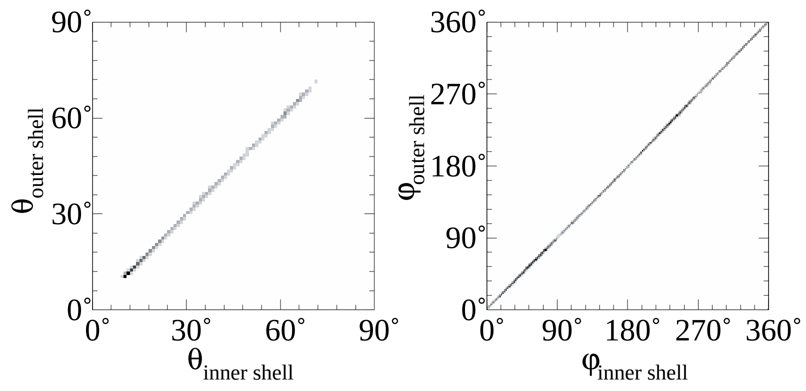

Fig. 7. Correlation of polar and azimuthal angle of elastic p–p events as measured by inner and outer detector shell

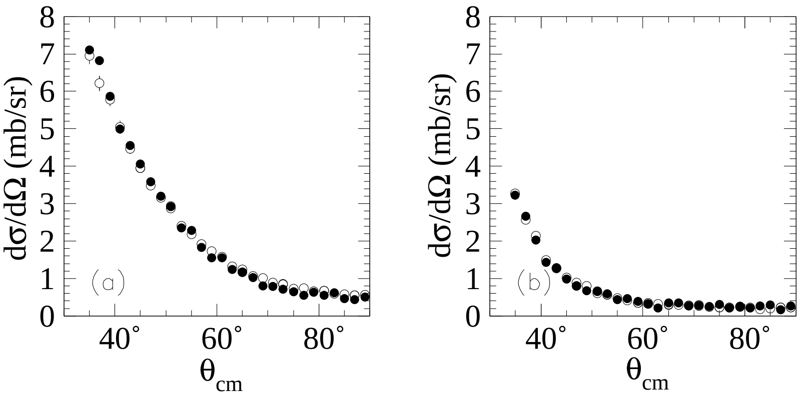

Fig. 8. Angular distributions of the spin-averaged p–p elastic cross section $\mathrm{d}\sigma/\mathrm{d}\Omega$ in the center of mass. Open symbols: data taken with the outer shell of the EDDA detector [1], filled symbols: data taken with the inner shell (helical fiber array). Energy intervals: (a): T = (1000±50) MeV, (b): T = (2000±50) MeV

was tested against the outer EDDA detector shell, measuring proton-proton elastic scattering cross sections with both shells operating independently from one another. These measurements were done with a narrow (2 - 3 mm FWHM) COSY beam on a CH_2 fiber target (4×5 μm^2 diameter), so that the reaction vertex was rather accurately known. The data obtained from the helical fiber array can then be compared to that resulting from the outer EDDA detector shell. Figure 7 gives such a comparison on an event by event basis, correlating the polar angles (Θ) and the azimuthal angles (φ). They are in agreement with one another within the angular resolution ($\approx 1°$). Fig. 8 compares the angular distributions of cross sections. They agree with one another within few percent. This agreement renders the helical fiber array fully functional. The detection efficiency of the helical fiber array was found to be 96 % with only a negligible dependance on angle and beam energy.

7 Summary and Conclusions

A helical scintillating fiber hodoscope consisting of 640 scintillating fibers was developed for the internal target experiment EDDA at the Cooler Synchrotron COSY. The scintillating fibers are arranged in four layers surrounding the beam pipe. They are helically wound in opposing directions and read out individually, using multichannel photomultipliers and the PCOS III system. Test measurements show that 99 % of all detector channels work satisfactorily. The detection efficiency was measured to be 96 % with a minute energy and angle dependence. The angular resolution is about $1°$ in Θ and φ. The helical scintillating fiber array is now routinely employed for vertex reconstruction in the EDDA experiment, as necessitated by the use of a polarized atomic beam target. In conjunction with the outer detector shell - a cylindrical array of scintillator bars and rings- it provides an r.m.s. resolution of 1.3 mm in vertex position, and concurrent determination of profiles of both the target and the accelerator beam. Stability in operation and unambiguity in the interpretation of data rest crucially with the absence of crosstalk and the uniformity of signal amplitudes.

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