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A SCINTILLATING FIBRE HODOSCOPE WITH AVALANCHE PHOTODIODE READOUT¹

W. Brückner, M. Godbersen, Th. Kallakowsky, R. Michaels,
S. Paul, B. Povh, K. Röhrich²

Max Planck Institut für Kernphysik
Heidelberg, Fed. Rep. Germany

Abstract

We have built a scintillating fibre hodoscope with rectangular fibres of $1.0 \times 0.5 \text{ mm}^2$ cross section coupled to avalanche photodiodes operated in the 'Geiger' mode. A total of 64 fibres have been arranged in 4 layers to investigate resolution and to obtain high efficiency and negligible cross talk for a special set of fibres. In this paper we describe the advantages and problems associated with such a readout and present results from a test run.

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²present address IKP, KFA Jülich, FRG

1 Introduction

One important issue of the new hyperon beam experiment at CERN (WA89) is the study of the flavour dependence of charm production [1]. Using Σ^- and Ξ^- as projectiles we want to study the dynamics of heavy flavour production on nuclear targets. As the hyperon beam contains Σ and Ξ at a ratio of about 20:1 the task consists in tagging online Ξ^- at high momenta. The low charm production cross section demands a very efficient detector to make full use of the Ξ^- in the beam. Owing to the small $\Sigma - \Xi$ mass difference such a tagging can only be achieved by means of a fast ring imaging Cerenkov counter (RICH). However, the CERN hyperon beam, which for this purpose will be operated at a momentum of 270 GeV/c, has a wide momentum acceptance of $\pm 10\%$ which can be translated into $d\beta/\beta$ of 6.0×10^{-6} . At a fixed momentum of 270 GeV/c the relative difference in velocity between Σ^- and Ξ^- is only 1.7×10^{-6} . The need of a fast determination ($< 2 \mu s$) of the particle momentum is evident and its precision should be better than 1 % which is determined by the resolution of the Cerenkov counter. A fast and highly resolving tracking device is therefore necessary.

Currently the new hyperon beam is produced by a 450 GeV/c proton beam from the CERN SPS impinging on a 50 cm long beryllium target of 2 mm diameter. Negatively charged secondary particles are extracted by means of a magnetic beam channel (fig. 1) providing at present a central beam momentum of 350 GeV/c. The beam has an intensity of 8×10^5 particles per spill (2.4 s) and is composed out of π and Σ ($\approx 2:1$) with some 'impurities' of K, Ξ and Ω .

Every momentum measurement requires a dispersive element in between the measurements of the particle positions. Because the high particle flux emerging from the beam dump in the first hyperon beam magnet forbids a position measurement behind the first magnet, the only place for a fast high resolution detector is the gap between the last two magnets. The necessity of a 1 % precision in the momentum determination requires here a position measurement of better than 250 μm if the outgoing track is measured with an accuracy of 50 μm which will be achieved by a pair of microstrip detectors.

The high particle flux expected at this point ($\approx 10^7$ in the beam spot) and the large background make scintillating fibres an ideal tool. However, the very confined space due to shielding blocks and the high magnetic stray fields lead us to avoid the use of photomultipliers for the read out of such fibres. In searching for a small size replacement avalanche photo diodes seemed to be the ideal devices.

2 Avalanche Photodiodes

The main disadvantage of common photodiodes in comparison with other light detectors is their lack of intrinsic amplification for single photon detection. Avalanche photodiodes which are characterized by an internal gain based on 'thrust ionization' of the charged carriers traversing a strong electric field in the depletion region can overcome this disadvantage.

Fig. 2 shows a cross section of an avalanche photodiode (APD) with a 'reach through structure' [2]. On one side of a silicon substrate with a low concentration of free carriers a p-type diffusion is followed by an n-type to build the avalanche region whereas on the other side the entrance for the light is p+ doped. Applying a reverse bias voltage of 5-10% less than the breakdown threshold the depletion layer of the pn region will 'reach through' to the substrate and another relatively small increase of the voltage will deplete the whole region up to the p+ contact. The electric field in this region will cause an e^- created by the

absorption of a photon to drift with saturated velocity to the pn junction. Here the very high field (4×10^5 V/cm²) provides amplification of up to 250 when operating the device with reverse bias voltage close to breakthrough.

For a very selected class of crystals of very high purity it is even possible to drive the bias voltage far above the breakdown point. The device enters the 'Geiger' mode with amplifications up to 10^7 . This very non linear process leads to a unique output pulse height which is in first order independent of the number of primary electron hole pairs. The avalanche may be quenched in a 'passive' way by limiting the latching current to 50 μ A by means of a resistor matched to the applied voltage or 'active' by reducing the bias voltage for a fraction of a microsecond [3].

At room temperature the dead time of the APD is mainly governed by the RC of the circuit where R is the current limiting resistor to protect the APD and C is the capacitance of the device. Typical values for R are 220 k Ω and C = 1.6 pF for the largest obtainable APD which can be driven in the 'Geiger' mode with an active surface of 0.2 mm². Fig. 3 shows the simple circuit with passive quenching used for the readout of an APD (30902S RCA). Signals of typically -300 mV with a risetime of 4 ns are obtained at C2. The dead time of low noise selected devices is about 800 ns, after which the signal height rises above the discriminator threshold, hinting that the capacitance of the diode might be higher than the nominal 1.6 pF. Full signal height is obtained only after a few microseconds.

For the experiment we expect a beam rate of approximately 10^7 particles per 2.4 s distributed over the beam size ($\varnothing \approx 2$ cm). Using 0.5 mm wide fibres the signal rate per channel would be of the order of 100 kHz and the loss due to a 1 μ s deadtime $\approx 10\%$. In a first step this is tolerated and possible improvements by 'active quenching' are not investigated here.

The operation in the 'Geiger' mode leads necessarily to a high thermally induced dark count rate, which cannot be discriminated against the signal by means of the pulseheight. This dark count rate increases linearly (~ 600 Hz/V) with the operating voltage (10-25 V above V_{Br}) reaching values of a few 10^4 counts/s with a threshold of 60 mV at room temperature (fig. 4). Cooling the device in principle reduces this rate, however also leads to a lengthening of the recovering time after a breakthrough due to a reduced mobility of the holes in the crystal.

The spectral response of an APD, shown in fig. 5a, is determined by the absorption of light in the depleted region from where electrons will drift to the amplification zone. Commercial APD's show a drop of efficiency towards shorter wavelengths which in part is caused by the addition of an antireflection coating. Omitting this coating increases the efficiency in the region between 500 and 600 nm, where most wavelengthshifters have their emission maximum. The quantum efficiency should then exceed 50%, but as not every electron created by the absorption of a photon is able to trigger an avalanche, the efficiency has still to be folded with the probability of creating an avalanche from a primary electron hole pair (fig. 5b). Applying a reverse voltage of 15-20 V above threshold the overall detection efficiency for a single photon should be about 25-30%.

Figure 6 shows as a function of the applied voltage the variation of efficiency. The efficiency was measured with a test set-up described in the following chapter. The distribution is characterized by a 10% increase of efficiency when raising the voltage from 8 to 14 V above threshold ($V_{Br} = 243$ V). The increase is followed by a rather broad maximum in the range of 14 to 21 V above V_{Br} . Raising the voltage further leads to a decline of the efficiency.

3 Fibres and coupling

Minimum ionizing particles traversing a 1 mm thick scintillating fibre generate about 2000 photons of which only 3.1% ($\sim 4\%$ in fibres with rectangular cross section [4]) are trapped in the fibre and propagate to one end. With attenuation lengths of more than 1 m for plastic scintillating fibres the losses due to damping are of minor importance in the 25 cm long fibres.

In addition to the shape and light output of a fibre, the mechanical coupling of the fibre to the active surface of the diodes is crucial (fig. 7). As normal APD's have a 1.27 mm gap between the entrance window and the active surface, light entering the APD through the sealing window will undergo refraction leading to a larger virtual lightspot. The insertion of a light guide from the window to just above the crystal reduces this effect.

The choice of the fibre type is governed by the spectral response of the APD and fibres emitting above 500 nm seemed most favourable. Four different fibre types¹ of round cross section ($\varnothing$ 1 mm) with differences in the wavelength of their emission maximum have been tested. They are less favorable than fibres with a rectangular cross section of $1 \times 0.5 \text{ mm}^2$ used in the final set-up, because in round fibres fewer photons are created due to a shorter mean path length for the passing particles, less light is collected and the coupling efficiency to the diode given by the surface matching between fibre cross section and active area of the APD is lower.

The test set-up consists of a ^{106}Ru β -ray source, a collimator and a scintillator with a thin copper absorber in front. The fibre/APD combination to be tested is placed together with another fibre in the collimator. The second fibre, also read out via an APD, and the photomultiplier at the scintillator give the trigger and define a passing minimum ionizing electron (fig. 8a).

The test results are listed in table 1. As expected the 3-HF fibre, of which the emission spectrum is adopted best to the spectral sensitivity of the diode, is superior to the others. The bad performance of the (S103) fibre might be explained by the fact that it was not yet fully developed and commercially not available.

The efficiencies could be increased by aluminizing the end of the fibres opposite to the APD, thereby regaining part of the scintillation light which is emitted in the 'wrong' direction.

After placing a third fibre into the collimator of the channel (fig. 8b) and including it in the e^- trigger to improve the definition of the electron the measurements were repeated using fibres with a rectangular cross section $1.0 \times 0.5 \text{ mm}^2$ of the 3-HF type. For single fibres we obtained efficiencies of more than 80%. Taking again only one fibre to define the trigger we measured efficiencies of more than 90% for the 'Ored' response of the other 2 fibres (table 2).

We have also investigated the possibility of reading out the fibre on both sides. The efficiencies and the noise rates increased drastically, however, more than expected from statistical arguments alone. Using the time information from both APD's and illuminating the fibre at different distances from the ends, we found that the increase was partly due to the light emission of one diode undergoing an avalanche which was detected by the other one. This light emission could be verified by placing an APD on an infrared sensitive film and operating the diode at high dark count rate. A double sided readout therefore also leads to an increased dark count rate for that fibre.

¹3HF, SCSN81T-Y7 from KURARAY, Japan and S101, S103 from OPTECTRON, France

4 The Prototype Hodoscope

For a first test run we arranged 64 channels in 4 rows of 16 fibres, each 25 cm long; 16 fibres were covered additionally with white paint to investigate crosstalk effects in comparison to the plain fibres. The avalanche photodiodes without antireflection coating were equipped with an internal lightguide (309021S RCA).

In each row the fibres were connected to the diodes by a bar of PVC, fitting on one side to the diodes whereas on the other side holes were drilled to centre the fibres to the sensitive area of the diodes. All APDs were directly mounted on printed circuit boards holding the passive quench circuit and the coupling capacitors. The distance between the frame holding the fibres and the circuit boards was shorter than a fibre length, so that the elastic tension of the fibres pressed them to the surfaces of the diodes. There was no optical grease used.

This whole assembly was then placed in a light tight box with thin black PVC windows for the beam. The signals of the APDs were passed through a discriminator and then fed into a TDC.

The hodoscope was tested in an electron beam from the CERN SPS (20 and 50 GeV/c). The beam is defined by 2 crossed finger counters, $2 \times 10 \text{ cm}^2$ in size. Two MWPCs with delay line readout are used to locate the impact point of the electron in the hodoscope (fig. 9).

Figure 10 shows a typical TDC spectrum for an APD signal. The time resolution is about 9 ns FWHM. An entry in the TDC within a window corresponding to 40 ns positioned around the peak of the distribution is regarded as a hit in the corresponding fibre.

The absolute position of each fibre in the array is obtained by fitting a Gaussian to the corresponding measurement provided by the MWPC, the FWHM of $\sim 1 \text{ mm}$ is due to the limited resolution of the chambers (fig. 11a). The residual of all channels is shown in fig. 11b. The average distance between the plain fibres was measured to be $440 \mu\text{m}$, the distance between the white fibres is $490 \mu\text{m}$ in agreement with measurements made with a micrometer. The relative shift of the rows were 480, 900 and $880 \mu\text{m}$.

For events in which the electrons pass the hodoscope the hit multiplicity distribution (fig. 12) of the 64 channels shows the expected mean value of 4, but also indicates inefficiencies and crosstalk. The same distribution for electrons missing the fibres shows a negligible background from random avalanche breakdowns.

In order to determine the efficiency of a specific channel in a given row a single hit in each of the three other rows and an overlap of the thus defined path with the investigated fibre were required. Efficiencies up to 92% in the central part of the hodoscope are found, exceeding the values obtained with the ^{106}Ru source. The efficiencies of the leftmost and rightmost channels would have to be determined in a different way and are not considered here (table 3).

Lower efficiency values ($< 70\%$) are due to an imprecision of the fibre diode connector. In a second test part of the connector bar in the fourth row was shifted by one position to the left not altering the position of fibres and diodes and using in the freed position (channel 9) a precision machined adapter instead. The efficiencies of the 7 channels reflect the same shift (last row of table 3), except in one channel which has obviously been improved just by means of a better fixation in the second try. The new adapter improved the efficiency of channel 9 from 61% to 87%.

These numbers are lower limits taking into account the systematic losses due to the thickness of the insensitive cladding ($\approx 5\%$, additionally $50 \mu\text{m}$ for the paint of the white fibres) and the fact that not in all cases a complete overlap of the defining path and the

corresponding fibre exists. The beam divergence of less than 2 mrad should be of no effect.

In the case of the plain fibres substantial crosstalk of 20-26% to either of the two neighbouring fibres could be observed (table 4). This effect could be reduced to 2-4% in the region where the neighbours are shielded against the light from the hit fibre by a layer of white paint. The variations in the numbers between neighbours in row 4 reflect the deviations in efficiency as discussed above.

5 Radiation Damage

The hodoscope was placed in the hyperon beam line of the WA89 experiment in its foreseen place as indicated in fig. 1 (H1). During the first 48 hours of operation the behavior of the diodes changed drastically. While the signal heights dropped to below 50 % of their original values, the noise rates increased up to a factor of 10. These new characteristics remained also after removal of the hodoscope. A heating procedure using hot air ($\sim 120^\circ\text{C}$) over a few days lead to a slight recovery of the noiserates (20 % decrease), but the original values could not be regained.

A radiation measurement in the beam line showed the expected low values of less than 150 neutrons / cm^2/s (> 6 MeV) and an upper limit of 900 slow neutrons / cm^2/s (< 10 MeV). Assuming a rate of 1000 n/ cm^2/s the integrated neutron flux accumulated within 48 hours is 2×10^8 n/ cm^2 which is 4 orders of magnitude below the threshold where other Si devices are affected [5]. The radiation level coming from photons and charged particles was found to be negligible as expected considering the shielding effect of the iron yokes of the magnets.

To confirm a possible radiation damage by neutrons, two well performing diodes were exposed to an integrated flux of 5×10^6 n/ cm^2 provided by a calibrated neutron source (Pu-Be $E_{\text{mean}}(\text{n}) \approx 4.3$ MeV). The dark count rates of both diodes increased permanently by a factor of 3 in comparison to the measurements made before.

Considering the total cross section of n-Si scattering, the size of the diode and the neutron flux, it seems that a few tens interactions already destroy the structure of the Si in a way that the extreme high electric field of the Geiger Mode is not anymore stable. Measurements of damaged diodes by the producer showed no change in performance in the normal avalanche mode applying a voltage below breakdown.

6 Conclusion

A prototype hodoscope built from scintillating fibres and read out with Avalanche Photo-diodes driven in the 'Geiger Mode' was tested in an e^- -beam. The signals of the diodes are characterized by a risetime of 4 ns, a pulseheight of -300 mV and a deadtime of ~ 800 ns for recovery back to threshold using a passive quenched circuit. Efficiencies for single channels of > 90 % were reached, crosstalk on the order of 20 % could be suppressed to 2-4 % by using fibres additionally covered with white paint. The noise of the hodoscope was negligible when triggering with a 40 ns gate.

Used in the hyperon beamline of WA89 the diodes, when driven in the 'Geiger' mode, showed a high sensitivity to radiation damage caused by neutrons.

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Table 1: Efficiencies of different scintillating fibres ($\varnothing$ 1 mm)

Fibre	Emission maximum	Efficiency [%]	Efficiency [%] aluminized
3-HF	530 nm	63	71
SCSN81T-Y7	500 nm	60	66
S101	430 nm	43	—
S103	510 nm	25	34

Table 2: Efficiencies of 7 rectangular 3-HF fibres ($0.5 \times 1.0 \text{ mm}^2$)

3-HF fibres	Efficiency [%]	
	APD1	APD2 or APD3
1	71.4	87.1
2	70.2	87.9
3	69.5	89.6
Aluminized	APD1	APD2 or APD3
4	83.9	93.3
5	84.6	90.9
6	83.3	93.4
7	80.3	94.2

Table 3: Efficiencies [%] of single channels in the prototype hodoscope

Row	Channel															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	50	91	89	87	92	90	90	92	89	85	86	76	78	-	-	-
2	-	86	89	82	81	84	86	86	79	78	73	83	81	74	-	-
3	-	-	78	82	85	85	87	86	81	88	88	65	85	84	85	-
4	-	-	86	53	83	54	82	59	61	80	78	79	68	67	31	-
4	-	-	43	83	31	85	71	91	87							

Table 4: Crosstalk of single channels in per cent

Row	Channel															
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1	15	16	26	29	27	27	32	25	25	25	10	3	2	-	-	-
2	-	31	20	25	22	23	24	23	21	20	11	4	3	3	-	-
3	-	-	15	23	26	25	25	24	28	24	15	3	2	2	2	-
4	-	-	7	26	7	26	9	18	17	17	17	3	3	3	1	-

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Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12