A FAST HIGH RESOLUTION BEAM HODOSCOPE USING SILICON MICROSTRIP DETECTORS

E. Heijne and P. Jarron
 EF-Division
 CERN, 1211 Geneva 23, Switzerland

Summary

Silicon detectors with a parallel strip pattern of 50 μm periodicity are used for the detection of high energy particles. Four detectors are mounted together in a beam hodoscope, which permits a measurement of the particle trajectory with a precision better than 20 μm . To each strip is connected a bipolar current sensitive preamplifier which provides a signal, shorter than 20 ns. It is shown that an optimal signal/noise ratio can be obtained if the signal is kept short throughout the signal processing chain. The noise after transmission over 100 m is 1300 electrons r.m.s.

With such a hodoscope single particle detection is possible for intensities in the range 10^6 - 10^9 cm^{-2} s^{-1} , and when used as a vertex detector, the parallel signal processing enables good particle separation in high multiplicity events.

Introduction

For the study of short-lived (10^{-13} s) charmed particles one has to develop new detection techniques which provide at the same time high spatial resolution (~ 10 μm), high multiplicity handling capability and high speed. Typical high energy beams for this type of study provide 10^5 - 10^7 particles in 1 s bursts on a target area of 10-50 mm^2 . The target can be a metal (Be or Cu) plate, a stack of nuclear emulsion, a small bubble chamber, or a telescopic arrangement of silicon detectors. Charmed particles decay after a short path length and give rise to one or more secondary vertices, with generally an increase of the number of emerging particles. For the reconstruction of such events both the position of the incoming particle and the directions of the emerging particles have to be known with high precision in the target region. The usual spectrometers or bubble chambers do not provide enough precision. By placing thin silicon microstrip detectors in the interaction region, the required precision will probably be obtained, and high event rates can be accepted. The main difference between a beam hodoscope in front of the target and a vertex detector, is the required detecting area, which has to increase rapidly with the distance behind the target.

Fig. 1: The masks and the mounting used for the vacuum evaporation of a strip pattern on silicon surface barrier detectors. The right-hand mask is used for the reinforcement of the contacts on the epoxy edge.

Fig. 2: Aluminium strips on the silicon surface, obtained by evaporation through the mask shown in fig. 1. The periodicity of the strips is 50 μm , and the contact to the printed circuit support is alternatingly made to the left or to the right, so that there is one contact every 100 μm . This contact density is already at the limit of conventional ultrasonic wire bonding.

Detectors

Silicon strip detectors have been used for position sensitive detection since a long time, but the necessity of a large number of electronic amplifier channels is a considerable drawback. Alternative solutions however are not applicable in the case of high energy experiments because of the very small signals delivered by minimum ionizing particles, because of the high rates and the need to detect up to 10 or 20 simultaneous particles which are close together. The strip detector becomes an interesting device for this application if the strip width can be made one order of magnitude smaller than what had been obtained so far (.5 to 1 mm) and if the cost of an amplifier channel can be reduced by two orders of magnitude, compared to a standard spectrometry channel for a solid state detector.

Such a microstrip detector, with 100 strips and a pitch of 200 μm was evaluated in a high energy particle beam, using a bipolar current sensitive preamplifier, which is simple and rather cheap.

The detectors now made for the beam hodoscope have 100 or 200 strips, but with only 50 μm pitch. Using the surface barrier technology, detectors were manufactured in collaboration with Enertec-Schlumberger (France), by evaporation of aluminium strips through a proximity metal mask, on the ohmic contact side of a 400 μm thick silicon wafer. In fig. 1 a picture is shown of the masks and the mounting used during evaporation. In fig. 2 one sees the image of the aluminium strips on the silicon. The actual width of these strips is determined by the relative distances to the silicon of the evaporation source and the metal mask. But it was checked once more that there exist no dead regions between the strips, so that the detection efficiency is

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essentially 100%. Contacts to the strips are made at the same time by extending the thin aluminium strips over the conventional epoxy edge passivation, to corresponding pads on the printed circuit board, which serves as detector support. A complete detector is shown in fig. 3, together with some preamplifiers and amplifier-line-drivers.

Fig. 3: A 50 μm pitch surface barrier microstrip detector with 100 strips. One sees the double connector arrangement with fine flexible wires, which avoid mechanical coupling of electronics and detector support. Also shown are dual preamplifier modules (in the middle) and amplifier-line drivers (to the sides). The height of these modules is about 25.4 mm, thickness is 4.5 mm.

Not only surface barrier detectors were made for the hodoscope but also 50 μm pitch planar detectors. This type of microstrip detector, manufactured also by Enertec, following the process developed by Kemmer,² is described in more detail elsewhere in these proceedings³. The strip structure on these detectors is made on the rectifying side, and is more regular than what can be achieved with the stretched metal mask. The contacts are made with ultrasonic bonding of aluminium wire, which results in a more reliable contact, but one bonding every 100 μm is near the limit of this technology. The leakage current of such detectors is typically .2 μA compared to 1-2 μA for the surface barrier detectors, and also the detector noise is much lower. The oxide passivation between the strips creates a very high electrical resistance, which is of the order of 1 G Ω , measured via the current which flows if a differential voltage is applied between two strips when the whole detector is biased at normal operation voltage. A similar measurement on our surface barrier detectors yields values around 100 k Ω . Moreover, in the latter case a large spread in values for different detectors is found, although values between several strips on the same detector are rather uniform. The resistance between strips in the case of surface barrier detectors is related to surface states, which can be less well controlled. The lower resistance on the surface barriers accounts for increased noise and also for a higher proportion of double hits via charge division in a small part of the interstrip region.

In comparing the surface barrier and planar microstrip detectors, it becomes clear that these planar detectors have many advantages over the surface barrier microstrip detectors. But the accumulation of charge in the planar oxide as a result of intense irradiation might represent a

problem. If the detector is carefully designed, a repeated annealing could probably solve this problem.

The Mechanical Mounting

The mounting of the detector is nearly independent of the attached electronics. The connections are made with .1 mm diameter flying insulated copper wires. The electronic modules near the detector contain the preamplifiers and the amplifier-line-drivers. They are exchangeable on separately fixed supports, as can be seen in fig. 4. Each module contains 48 channels and on one support two modules are foreseen at either side. Therefore, one detector with 192 strips or two detectors with 96 strips each, can be accommodated. The two detectors with 100 strips each are mounted on quartz blocks with an optically flat surface, such that the 50 μm strip structures have a parallel shift of half a period, 25 μm . The quartz blocks are clamped on a marble, with only 2 mm spacing between the detector surfaces. The marble is independent from the electronics supports, and fits in the central space in fig. 4. A second set of two detectors and electronics is foreseen at 64 mm downstream of the first set, on the same marble, which furthermore supports the target and the silicon microstrip vertex detectors. A complete set-up is sketched in fig. 5.

Fig. 4: Mechanical mounting of the 48-channel preamplifier-driver modules next to the detector, which is shown here without its separated precision support. The two electronic modules below are the 12-channel receiver-driver modules which receive the signals after 40 m of twisted pair cable.

Fig. 5: Sketch of the arrangement of beam hodoscope, target and vertex detectors on a common support table.

The Signal Processing

The signal rise-time from the beam hodoscope should permit a timing comparable to the performance of a scintillator and photomultiplier. With a thin detector (200 μm - 400 μm) values below 10ns are obtained, with a time jitter of less than 1 ns. Also the signals should be short, so that a high counting rate can be handled. The electronics design therefore aims at the best compromise between speed and the signal to noise ratio. Moreover, the resulting electronics should be simple and cheap, in view of the numerous channels. Also a low power dissipation is important.

In fig. 6 a diagram is shown of the entire signal processing chain. Immediately besides the detector are located the preamplifier and the amplifier-line-driver, which provides a 100 mV signal on the 40 m long twisted pair cable. A receiver module in the electronics barrack provides two outputs. One is an analog signal which is transmitted over another 50 m of twisted pair cable to a transformer, which couples with a 120 Ω /50 Ω impedance adaptation into a LRS 2249 A charge sensitive ADC. The second output is an ECL logic signal, resulting from internal discrimination. This logic output can be stored in a pattern unit, so that both the analog and digital information from the detectors can be read if an event trigger decision has been taken. Besides, the logic output can also be used immediately for such a trigger decision.

Fig. 6: The electronic signal processing. The typical signal levels for a minimum ionizing particle are indicated.

The Preamplifier

A current sensitive preamplifier as shown in figs 7 and 3 was built, using a bipolar microwave transistor at the input. This transistor has a current gain of 100 and a transition frequency of 3 to 5 GHz. In the current sensitive configuration a parallel noise results from the thermal noise contribution of the 10 k Ω feedback resistor R_p and the shot noise on the base current of $\sim 5\mu\text{A}$ in this transistor. The noise optimization is possible if the weighting function is chosen such that the resulting noise contains equal contributions of the parallel and series noise. This can be obtained via an adjustment of the collector current.

Radeka has studied⁴ the equivalent noise charge (ENC). In our case a Gaussian filtering is obtained by the combination of the different poles in the transfer functions of the preamplifier, amplifier-driver, amplifier-receiver and the response of the cable, which are compensated by a "pole-zero cancellation". Globally, the filtering is nearly Gaussian, so that according to Radeka's study

$$(\text{ENC})^2 = W_{os} C_{in}^2 \left(I_1 + \frac{1}{\tau_c} I_2 \right)$$

MICROSTRIP DETECTOR PREAMPLIFIER

Fig. 7: Circuit diagram of the preamplifier

I_1 and I_2 are given by the weighting functions

$$I_1 = \int_{-\infty}^{+\infty} [w'(t)]^2 dt \quad \text{for the series noise}$$

$$I_2 = \int_{-\infty}^{+\infty} [w''(t)]^2 dt \quad \text{for the parallel noise}$$

$$\tau_c = C_{in} \sqrt{R_s R_p}, \quad W_{os} = 4 kT R_s$$

With our actual values we find for the parallel noise

$$R_p = 7 \text{ k}\Omega$$

and for the series noise, with the base spreading resistance $R_{bb'}$

$$R_s = R_{bb'} + \frac{kT}{qI_e} = 75 \Omega$$

The input capacitance

$$C_{in} = C_{det} + C_{stray} + C_{preampli} + C_{interstrip}$$

amounts to about 15 pF, so that the time constant $\tau_c = 10.5 \text{ ns}$

In the optimal Gaussian filtering condition we find then the sigma value σ_G, opt .

$$\sigma_{G,\text{opt}} = 2.63 \tau_c \cdot 3.72 = \frac{\tau_c}{\sqrt{2}} = 7 \text{ ns}$$

Expressed as a full-width-half-maximum (FWHM) of the signal this gives 16.5 ns. The conclusion is therefore that in our case an optimum in noise performance can be obtained with a signal shaping of somewhat less than 20 ns.

The lowest attainable noise is determined by the input transistor and therefore an analysis was made of the noise performance of different transistors. Results obtained with a LRS 3157 charge multichannel analyzer with 40 ns gating time are shown as a function of the input capacitance C_{in} in fig. 8 for the transistor BFT 25 and the transistors NEC 578 and NEC 021. For C_{in} lower than 15 pF they are equally good but at higher C_{in} the NEC are superior, with 30 e r.m.s. per pF against 50 e r.m.s. per pF for the BFT 25.

In an earlier study⁵ the performance of several configurations, each time using the same NEC 578 input transistor, has been described. It will depend on the particular application, which configuration is most appropriate. Advantages of the current sensitive preamplifier are the short shaping time, the simplicity and the low power dissipation.

Fig. 8: Comparison of noise characteristics as a function of input capacitance for three different bipolar transistors, BFT 25, NEC 578 and NEC 021. Data are normalized for the effective weighting function.

Fast Signal Transmission

As shown before, the optimal noise performance requires a short filtering time, and an effective method is needed to send the signals over 50 to 100 m of multi twisted pair cables. The cable response to a step voltage is shown in fig. 9. The diameter of the wires is .22 mm² and the characteristic impedance is 120 Ω, length is 50 m. Three time constants can be distinguished in this response, corresponding to three excitation modes. Applying now a signal of 12 ns duration, generated by the detector-amplifier, it is possible to use only the first mode, corresponding to the highest pole. A fast signal is then transmitted, as is required for the conservation of a good signal/noise, as well as for good timing. The price to be paid is a rather strong attenuation of about a factor 2.5 (for 50 m).

Fig. 9: Response of 50 m of twisted pair cable to the application of a step voltage.

Fig. 10: Signal obtained after pole-zero cancellation, transmitted over 50 m distance, at the input of the discriminator.

The differential receiver amplifier built around the μ A 733 video amplifier, provides a gain of 10x and drives an analog output and a discriminator for a fast logic signal. The signal delivered by the receiver is shown in fig. 10. The asymmetry can be corrected with a pole-zero cancellation, so that a nearly Gaussian signal is obtained. An equivalent noise charge of 1100 electrons r.m.s. was measured on the discriminator signal and 1400 e r.m.s. on the ADC charge signal, with a gating time of 40 ns.

The complete detector-amplifier chain can be calibrated in energy with a 122 keV ⁵⁷Co gamma source. Its energy is near to the most probable energy deposit by minimum ionizing particles in 400 μm of Si (~ 27 keV) per 100 μm of Si). In fig. 11 a signal is shown of such a gamma event. With the absolute energy calibration one can make a check on the effective energy deposit. For a given planar detector of 280 μm thickness the peak of the Landau distribution is located at 76 keV, which corresponds to an energy deposit of 27.1 keV per 100 μm, well in agreement with previous measurements on surface barrier detectors. The width of the distribution of noise signals around the pedestal can be used to determine the electronic noise, which is anyway less important than the Landau fluctuations on the signals of minimum ionizing particles. For the same planar detector a FWHM of 17 keV was found for the pedestal width compared to a 18 keV FWHM of the ⁵⁷Co photopeak. The width of the Landau distribution is 30 keV or 40% of its value.

Fig. 11 Signal of 122 keV gamma source of ⁵⁷Co, at the output of the preamplifier, before shaping (10ns/div).

Conclusion

The hodoscope has not been installed in the 200 GeV/c beam yet, so that results on the reconstruction precision are not available. But single detectors were tested in a 16 GeV/c test beam and their precision was compared with high precision wires chambers with centre of gravity read-out on a subdivided cathode. The residu, i.e. the difference between the position calculated from the chamber information and the position of the responding strip, is plotted in fig. 12. The FWHM of this residu distribution is 140 μm , which corresponds to a sigma of 60 μm , and is mostly determined by the chamber precision. It becomes apparent that a better resolution is needed to evaluate adequately these microstrip detectors, but it is always important to eliminate possible systematic errors by comparing basically different detectors.

A phenomenon in the microstrip detectors which requires further study is the double (or multiple) hit. A number of adjacent hits are called a cluster. About 10% of the events have two or more clusters, most spurious "hits" in this case are noise, related to the choice of the definition of "hit" as a signal which exceeds the pedestal by 3 sigma values of the pedestal noise distribution (PND). True double hits, adjacent in one cluster, occur in 5% of the events for a planar detector and in $\sim 25\%$ of the events for a surface barrier detector. Part of these double hits are caused by charge division between two strips. It is not yet clear if in this case one has a loss of resolution, or if an improved precision can be obtained from the comparison of the signal heights on both strips.

The development of microstrip detectors and related electronics will serve new experiments in high energy physics, but it may also have an impact on particle detection in other fields.

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Fig. 12:

Residu of predicted and observed position on a 50 μm pitch surface barrier detector. The width of one microstrip detector element is indicated. Only events with one single hit were taken into consideration, so that about 35% of the events was rejected.