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A. Codino:

MULTIPLE MEASUREMENTS OF TIME OF FLIGHT, POSITION AND ENERGY DEPOSIT OF IONIZING PARTICLES BY SOLID STATE DETECTORS

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Multiple measurements of time of flight, position and energy deposit of ionizing particles by solid state detectors.

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A telescope made of silicon strip detectors performing simultaneous measurements of position, time and energy deposit has been constructed and operated. The telescope has been tested with a pion beam of 4 GeV/c at the CERN Proton Synchrotron. The intrinsic time resolution of the telescope measured in the beam test is 61±7 ps. This unprecedented time resolution is achieved by the multiple sampling of the time of flight. Future developements of this telescope aiming at the construction of a new, analogous instrument of large sensitive area are considered (LATIN project).

1. Introduction

Time-of-flight (TOF) techniques have been long utilized in various detector configurations devoted to High Energy Physics, Nuclear Physics, Cosmic Ray Physics and similar disciplines for particle identification, to trigger data acquisition and for fast timing. Solid state detectors (silicon, germanium, gallium arsenide and diamond) [1,2,3,4], gas detectors [5,6] and the classical configuration scintillator-photomultiplier have been successfully operated in various experimental configurations. Time resolutions close to 100 ps have been achieved in detector prototypes while instruments employed in physics experiments have time resolutions in the range from 150 to 300 ps.

We have developed a new detector prototype made of silicon strip detectors where each hodoscope (strip) provides simultaneous measurements of:

(1) time of flight;
(2) specific ionization (dE/dx);
(3) position.

This prototype is a new instrument which may identify elementary particles ($\pi^{\pm}$, $k^{\pm}$ and protons) and nuclides at intermediate energies avoiding the use of Cherenkov counters, magnet spectrometers, scintillator-photomultiplier counters and other ancillary detectors.

This prototype has two major characteristics:

(1) capability of multiple sampling of the time of flight and energy deposit of the ionizing particle which entails better resolutions campared to those attainable by a single sampling. Multiple measurements are possible because the detector is composed of 8 silicon detector planes.

(2) capability of measuring the energy of the incident particles and performing their identification. The useful energy ranges in various experimental conditions for nuclides and elementary particles are computed and reported in the LATIN proposal [7].

The detector is described in Section 2. The preliminary data analysis for the evaluation of the time resolution by using the technique of the multiple sampling for measuring time intervals is in Section 3. Future developements of the instrument in view of its application to physics experiments are in Section 4. Finally, in Section 5, the estimate of time resolution attainable by solid state detectors of large sensitive area is reported.

2. The upgraded COSIDE telescope.

The COSIDE telescope [1,2,8,9] was modified from its previous version that was exposed to the hadron beam of Saturne II accelerator, at Saclay (France) in 1993. A detailed description of the COSIDE telescope may be found elsewhere [1]. The new telescope, called in this paper the upgraded

COSIDE telescope, has been exposed to the pion beam of the Proton Synchrotron (PS) at CERN in 1995.

The COSIDE detector is an instrument that measures the time of flight of ionizing particles. It consists of three matrices of silicon strip detectors contained in 3 boxes forming the 3 arms of the time-of-flight detector system. A matrix is made of two detector planes formed by 10 horizontal strips followed by 10 vertical strips. The cross dimensions of the silicon detectors are 2x2 cm^2, subdivided into 10 equal strips 2 mm wide, manufactured by Micron Semiconductor Srl, Sussex, England.

The upgraded COSIDE telescope shown in fig. 1 consists of only two arms, denoted here by α and β positioned at a distance of 895 mm along the beam line. Each arm is formed by 4 silicon detector planes with a sensitive area of 2x2 cm^2.

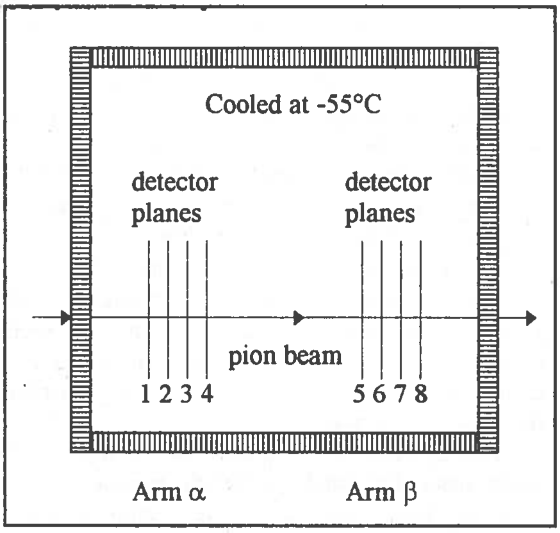

Figure 1. Schematic cross view of the upgraded COSIDE telescope tested with a pion beam of 4 GeV/c. Particles crossing the detector with normal incidence traverse 4 strips in the 4 detector planes (1,2,3,4) of the arm α and 4 strips in the 4 detector planes (5,6,7 and 8) in the arm β.

The silicon detectors of the new telescope are those utilized for the COSIDE telescope. The strip of two adjacent planes form an x-y grid. The new arrangement of the detector planes along the particle trajectory allows the multiple measurements of the time of flight.

Each readout chain for timing is composed of a current preamplifier, an insertional preamplifier, a constant fraction discriminator (CFD) and a time-to-digital converter (TDC). The signal from the insertional preamplifier is split into two routes. In the first route, which measures the energy deposit of the ionizing particle, the signal from the preamplifier is shaped and read by an ADC. The determination of the energy deposit allows the correlation between time of flight (determined by CFDs and TDCs) and pulse amplitude.

A gold-plated box, light tight, containing silicon wafers and electronic readout ensures electromagnetic shielding from the ambient noise. The prototype is operated at the temperature of -55 °C to reduce the electronic noise and the leakage current of the silicon detectors.

3. Evaluation of the time resolution.

The following data analysis is restricted to the detectors of the arm β.

Beam particles penetrating the 4 silicon layers of the arm β are registered by 4 independent electronic readout chains. The strip 6 of the detector plane 5 is used to start the data acquisition. Accordingly, 3 independent measurements of the time intervals are available for a single arm. The time resolutions for several pairs of hodoscopes of the arm β at the temperature of -55°C are shown in fig.2. The time resolutions in different pairs of hodoscopes are comprised between 90 ps and 145 ps and are similar to those obtained with electrons from ^{90}Sr source [2]. Note that pions traverse various sets of 4 strips (quadruplets) in the 4 detector planes of the arm β and not only one quadruplet. This is due to the finite emittance of the beam and its transverse dimensions of about 2 mm.

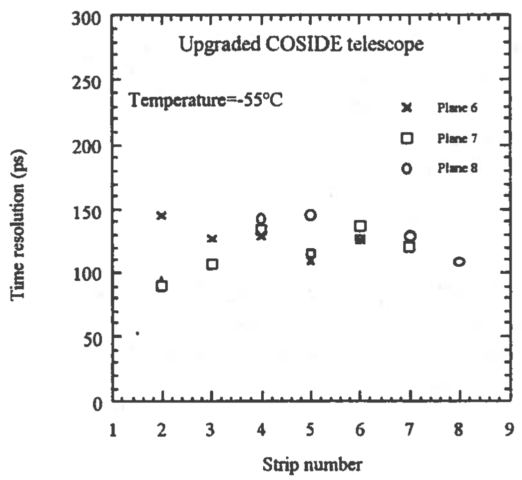

Figure 2. Time resolutions of several pairs of silicon hodoscopes of the upgraded COSIDE telescope traversed by charged pions of 4 GeV/c.

The procedure employed in the evaluation of the time resolution is described elsewhere [3] and is applied to the following quadruplet: strip 6, plane 5; strip 4, plane 6; strip 6, plane 7; strip 5, plane 8.

We denote by T_{12}, T_{13} and T_{14} as the time intervals elapsed when the pions travel from the plane 1 to the planes 2, 3 and 4, respectively (see fig. 1). Suitable delays between the 4 signals coming out from different strips of the quadruplet are introduced to ensure an appropriate range in the TDC. The standard deviations of the distributions of T_{12}, T_{13}, and T_{14} are, respectively, $\sigma_{12}=116$, $\sigma_{13}=110$ and $\sigma_{14}=134$ ps. The average time resolution, <T>, of the arm β is defined by the arithmetic mean:

$$\langle T\rangle = (T_{12} + T_{13} + T_{14})/3$$

The distribution of <T> for the selected quadruplet is shown in fig. 3. The standard deviation σ_T of this distribution is 84±7 ps. The intrinsic time resolution σ_1 for one hodoscope is

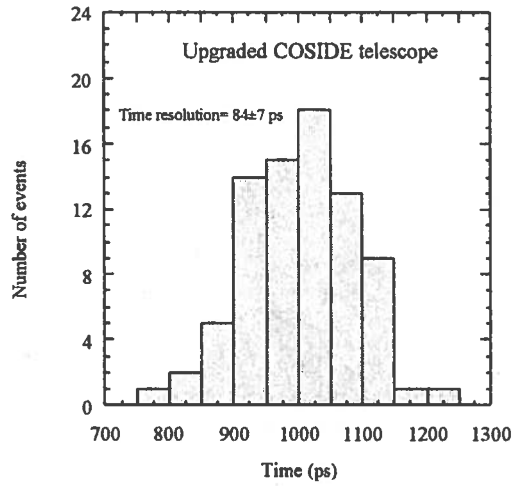

Fig.3 Distribution of the mean of 3 time intervals between the different detector planes of the arm β of the telescope.

obtained by dividing σ_T by $\sqrt{2}$ which gives 61±7 ps. The quoted error of 7 ps is the digitalization error of the TDC.

If the distributions of T_{12}, T_{13}, and T_{14} were interpolated by 3 gaussian functions normalized to the same means and with 3 equal standard deviations, σ, the distribution of the average, $(T_{12}+T_{13}+T_{14})/3$, would have a standard deviation $\sigma/\sqrt{3}$. Test beam data for the quadruplet mentioned above has a time resolution of 86 ps and an observed mean of the 3 standard deviations $(\sigma_{12}+\sigma_{13}+\sigma_{14})/3$ of 108 ps, giving $3\sigma_T/(\sigma_{12}+\sigma_{13}+\sigma_{14}) = 1.4$ to be compared with the ideal case considered above of 1.71.

The data analysis of the pion beam test including the two arms of the telescope is not yet completed.

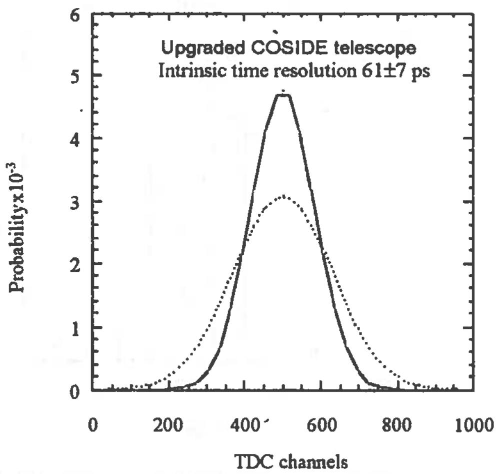

Figure 4. Time distribution of a pair of hodoscopes (dotted line) and the mean of 3 time intervals (solid line) for the arm β of the upgraded COSIDE telescope. The two curves are the probability distributions from gaussian fits of the experimental data. The average bin width of the TDC is 25 ps.

4. The LATIN project.

The intrinsic time resolution of 61±7 ps reached by the upgraded COSIDE telescope demonstrates that silicon strip detectors operated at -55°C may conveniently compete with scintillator-photomultiplier counters on the time resolution.

Position and dE/dx resolutions of silicon strip detectors are superior to those achievable with hybrid systems including scintillator-photomultiplier counters or spark chambers in conjunction with other detectors. Note that spark chambers do not measure the energy deposit of ionizing particles and that the time resolution is significantly larger than that quoted in test prototypes [5,6] because of the large tails present in TOF distributions, artificially excluded from the evaluation of the time resolution. The large area and very fine granularity apparatus with excellent TOF and energy resolution are usually achieved by using different detectors. For example, scintillator-photomultiplier counters have good time resolution but poor spatial resolution. Thus, multiwire proportional chambers or drift chambers usually complement scintillator-photomultiplier counters for position determination in a hybrid detector system. Note also that the charge dynamic range for scintillator-photomultiplier counters employed for time-of-flight measurements is very limited, impeding nuclide identification of numerous species and in broad energy intervals.

Silicon strip detectors performing time, position and dE/dx measurements have, however, two major disadvantages compared to other hybrid detector systems making the same measurements:

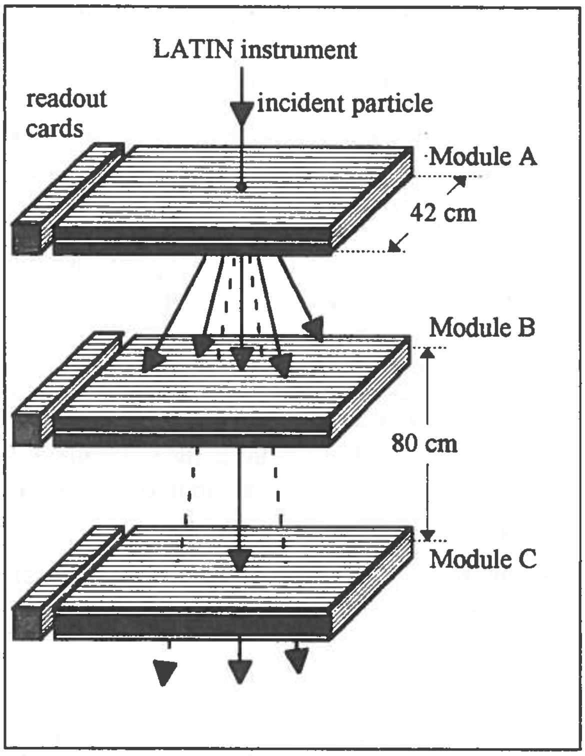

Figure 5. Layout and dimensions of a time-of-flight instrument of large area for nuclide and particle identification. The three modules A, B an C are the minimum number required to cross-check the time-of-flight resolutions of different hodoscopes.

(I) small sensitive area;
(II) high costs for the electronic readout system due to the large number of readout channels.

In order to solve these two problems, we have conceived the LATIN project (LATIN denotes Large Area TIming Network) [7].

An example of geometrical configuration of the LATIN instrument for a large area time-of-flight detector system with dE/dx and position capability is shown in fig. 5.

It consists of 3 equal modules A, B and C of nominal cross dimensions 42x42 cm^2 separated one another at a distance of 80 cm, which is the lever arm for the time of flight. Such a distance may be varied depending on the specific application involved and experimental constraints. Each module consists of 4 planes of solid state detectors with a total sensitive surface of 1764 cm^2 as depicted in fig. 6.

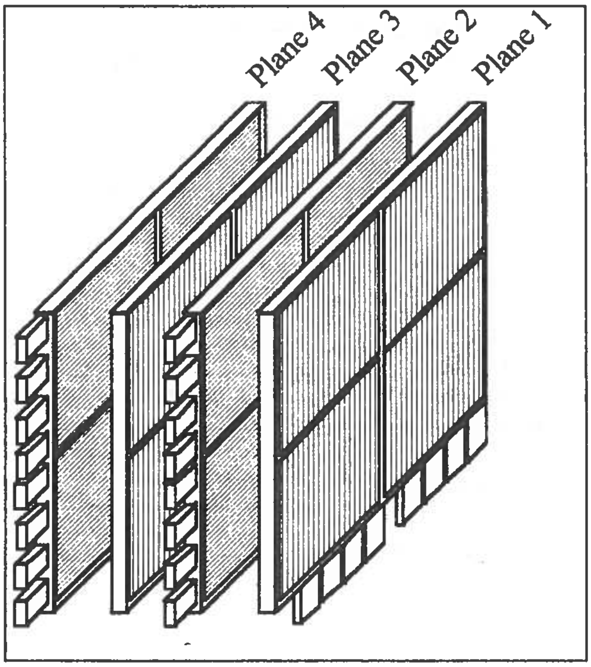

Figure 6. Dimensions and structure of one module of the LATIN detector. One module made of 4 detector planes will have 16 quadrants of cross dimensions 21x21 cm^2

Each plane in a module is equipped with solid state detectors, preamplifiers and readout cards including ADCs, discriminators and TDCs. The structure and dimensions of the silicon or gallium arsenide layers are displayed in fig. 7. Long strips, of about 20 cm, are obtained by a row of silicon wafers connected together as shown in fig. 7-b. The high capacitance of the hodoscopes, of about 40 pF, deteriorates the time resolution that may be achieved in short strips such as those used in the COSIDE telescope.

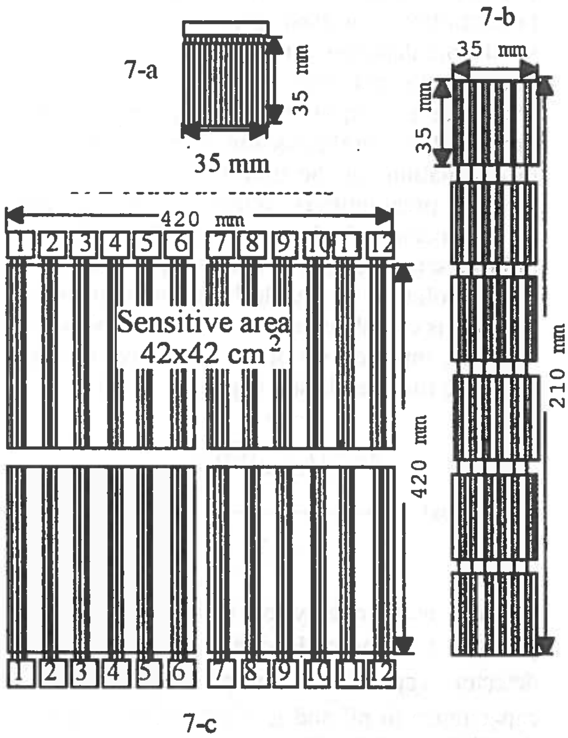

Figure 7. Spatial arrangement and dimensions of silicon wafers and strips in one module of the LATIN experiment.

7-a Silicon wafer of dimensions 3.5x3.5 cm^2.

7-b Chain of 6 silicon wafers forming strips 21 cm long.

7-c Total surface of 42x42 cm^2 of one plane of a module. There are 4 planes per module.

The detailed analysis of this deterioration is beyond the purpose of this paper. The LATIN project intends to preserve an excellent time resolution such as that of the upgraded COSIDE telescope in a large area detector. This may be primarily accomplished by constructing ultrafast, low noise preamplifiers.

5. Evaluation of the time resolution of a silicon detector telescope

The most critical element in the signal processing chain for TOF measurements is the preamplifier. Ultrafast preamplifiers to read out solid state detectors for time-of-flight determination may be divided into two classes: (I) low input resistance preamplifiers; (II) high input resistance preamplifiers. In this section are reported the results of calculations of the time resolution attainable by voltage preamplifiers (class II) for a detector capacitance of 45 pF appropriate for an instrument of large sensitive area as discussed in Section 4. The time resolution attainable by current preamplifiers (class I) is calculated in the LATIN proposal [7].

If the input device of a voltage preamplifier is a FET, the time resolution is given by [10]:

$$\sigma_T\,[\mathrm{ps}] = \frac{1.57\sqrt{\dfrac{\tau}{g}}\,(C_D+C_I)}{E}$$

where E is the energy lost in MeV by the ionizing particle, τ is the collection time in ns, C_D is the detector capacitance in pF, C_I is the input capacitance in pF and g is the transconductance of the FET in mA/V. The resulting time resolution for a silicon detector of thickness d is:

$$\sigma_T\,[\mathrm{ps}] = \frac{16.96}{\sqrt{g}\,(d[\mathrm{cm}])^{1.5}}$$

By using the detector dimensions of the LATIN proposal, a detector thickness of 500 μm and a typical transconductance of 50 mA/V a time resolution of 214 ps is computed.

Exceptional input devices with low noise or very large g, or small capacitance detectors may exhibit better time resolutions.
For a gallium arsenide detector under similar approximations and conditions we have found a computed time resolution of about 100 ps.

The time resolutions attainable by bipolar transistors used as input device of voltage preamplifiers are between 100 and 200 ps. Comparisons between time resolutions of gallium arsenide and silicon detectors read by the same preamplifiers also indicate that gallium arsenide detectors perform better [11].

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