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ELECTRONIC NOISE IN A SILICON DETECTOR TELESCOPE**

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Abstract

We have constructed a silicon detector time-of-flight spectrometer operating at low temperature with an overall time resolution of 115.2 ± 2.0 ps at -55 °C for minimum ionizing particle with unitary charge. We report the measurement of the overall time resolution of the telescope versus temperature in several relevant experimental conditions from -50 °C to 20 °C. An extensive experimental study of the noise components of the detector and of the electronic readout as a function of the temperature is also given. We present an analysis of the measured noise components in order to account for the improvement of time resolution when the temperature varies from 20 °C to -50 °C. Future developments of cold silicon strip detectors for time-of-flight determination are considered.

1. Introduction.

High resolution time-of-flight (TOF) measurements for long living elementary particles and nuclide identification have been employed in numerous experiments. The classical configuration scintillator photomultiplier is the most common experimental arrangement in Nuclear and Particle Physics. Spark chambers [1] and silicon solid state detectors [2] are also used in some experiments to meet specific requirements. Recently, reach-through silicon avalanche diodes have been operated as TOF detectors [3] for relativistic particles.

We developed the COSIDE¹ (COLD Silicon DETector) project aiming at the construction of a TOF apparatus made of silicon strip detectors and electronic readout operating at the temperature of -55 °C for TOF measurements in space experiments. The advantages of using cold silicon detectors and the cold electronic readout for time-of-flight measurements have been experimentally proved and are described elsewhere [4]. Here, we would like to mention that we also investigated the benefits of using cold silicon strip detectors as hodoscopes of a silicon calorimeter for space experiments [5]. The COSIDE apparatus was exposed, in October 1993, to a hadron beam at the accelerator Saturne II, Saclay (France). The response of the apparatus in test beam conditions is described in another paper [6].

Silicon detectors for TOF measurements have been long used in Nuclear Physics [7,8]. These detectors are usually optimized for high Z slow nuclei where the energy deposition is rather large. Our experiment is devoted to the development of the silicon TOF detectors for minimum ionizing particles with unitary charge. Note that the energy deposit of a minimum ionizing particle (MIP) with Z=1 in 300 μm detector thickness is about 100 keV while that of slow heavy ions may be a factor $10^2 - 10^3$ higher. Huge energy deposits yield large detector signals. Processing large signals for precise TOF measurements is easier than processing small signals like those originated by MIPs with Z=1.

Besides the main results on the dependence of the time resolution in a silicon strip telescope as a function of the temperature, this paper provides the measurement of the noise level in different experimental situations as a function of the temperature. These noise measurements constitute the basis to interpret the time resolution of silicon strip TOF telescope. They also provide a valuable indication on how to improve the time resolution below 100 ps for MIPs with Z=1. Finally, let us notice that the variation of the time resolution with temperature for a given silicon TOF instrument is difficult to be calculated unless known a posteriori [4].

¹ This experiment is funded by Istituto Nazionale di Fisica Nucleare (INFN), Italy.

2. Instrument description.

The COSIDE apparatus, described in detail in ref. [6], consists of three arms of silicon strip detectors maintained at temperatures varying from -55 to 20 °C. One arm, shown in fig.1, consists of two square silicon chips of dimensions 2 x 2 cm² and 250 μm thickness, segmented into 10 strips 0.2 x 2 cm² (3000 Å metallization thickness) manufactured by MICRON Semiconductor ltd. Sussex, England. Each silicon strip is connected to a current preamplifier specifically designed for this experiment [9]. The silicon wafers and the preamplifiers are enclosed in an electromagnetic shielding box² (7 mm thickness). This box is enclosed in another Faraday cage to improve the electromagnetic shielding. The whole system, detector and preamplifiers, is positioned in a 2000 liter climatic chamber manufactured by Angelantoni, Massa Martana, Perugia (Italy). The temperature may be adjusted from -55 °C up to 150 °C with the accuracy of ± 1 °C. The humidity level is under 10%.

The preamplifiers³ have been assembled using surface mounted devices operating in the military temperature range. These components are mounted on a printed circuit board designed and built according to the rules for high frequency circuit layout design. The rise-time of the preamplifier is less than 2 ns as measured by using a voltage test pulse with a rise-time of 200 ps. The preamplifier is composed of two transistor stages in a current-shunt feedback loop. The transistors (Philips BFQ67) are radio frequency, surface mounted device with $h_{FE} = 100$ and $f_T = 7.5$ GHz.

The preamplifier output is connected to the insertion amplifier, which is a two-stage integrated voltage amplifier having an overall gain of 60, a bandwidth of 320 MHz and input and output impedances of 50 Ω. The insertion amplifier is connected to the constant fraction discriminators (ORTEC 935) having a maximum time-walk of ±25 ps (FWHM) in the voltage range -50 mV up to -5 V. The logic pulses generated by the discriminators go to the stop inputs of the TDC for time measurement. We used a time-to-digital converter (TDC), Le Croy 2229 Mod. 400, having a nominal resolution of 30 ps/count. Careful calibration showed that the TDC time resolution is 24 ps/count instead of the nominal 30 ps/count.

The charge distribution deposited by electrons from the source ⁹⁰Sr in the COSIDE telescope has been measured by an ADC LeCroy 2249A and is reported in fig.2. The measurement has been performed by gating the ADC with a low threshold discriminator (Caen N224).



² Manufactured by Benzoni, Como (Italy).

³ Manufactured by Db2 electronics, Cuggiono, Milan (Italy).

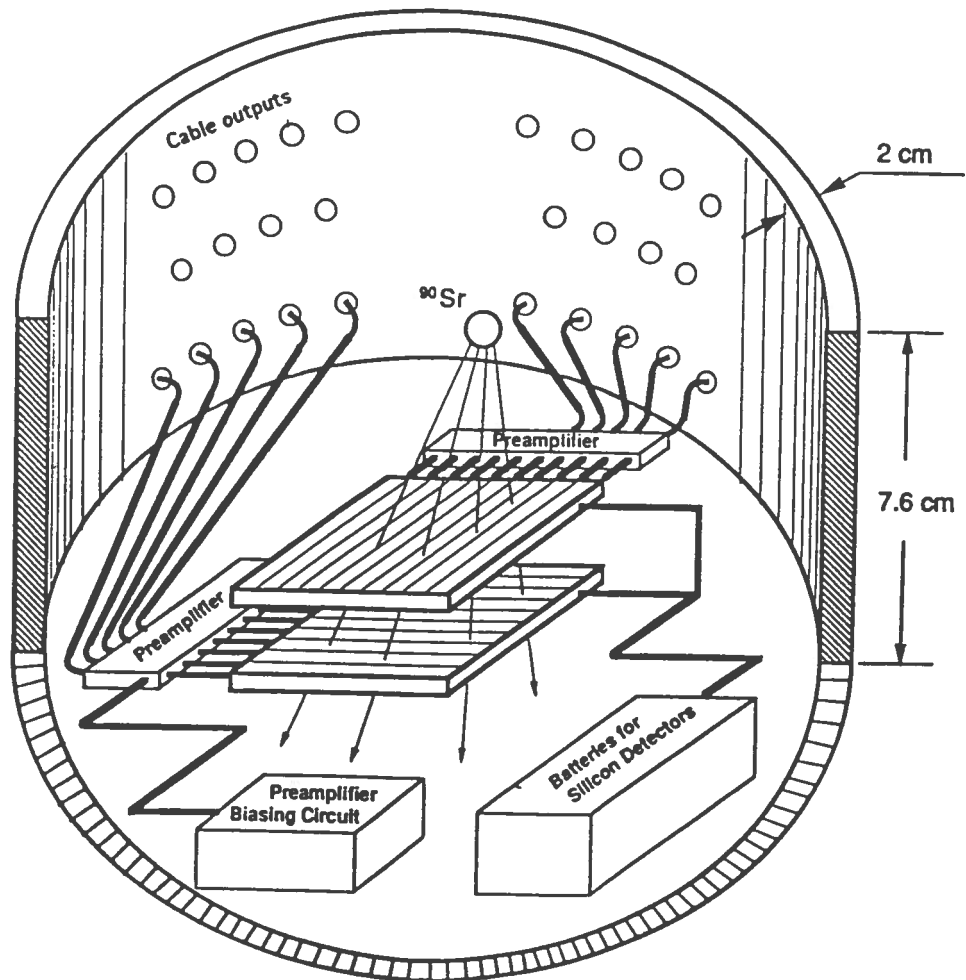


Fig. 1

Aluminum cylindrical box containing two silicon strip detectors, preamplifiers, batteries and the beta emitter ^{90}Sr . The box is used for electromagnetic shielding and is also light tight.

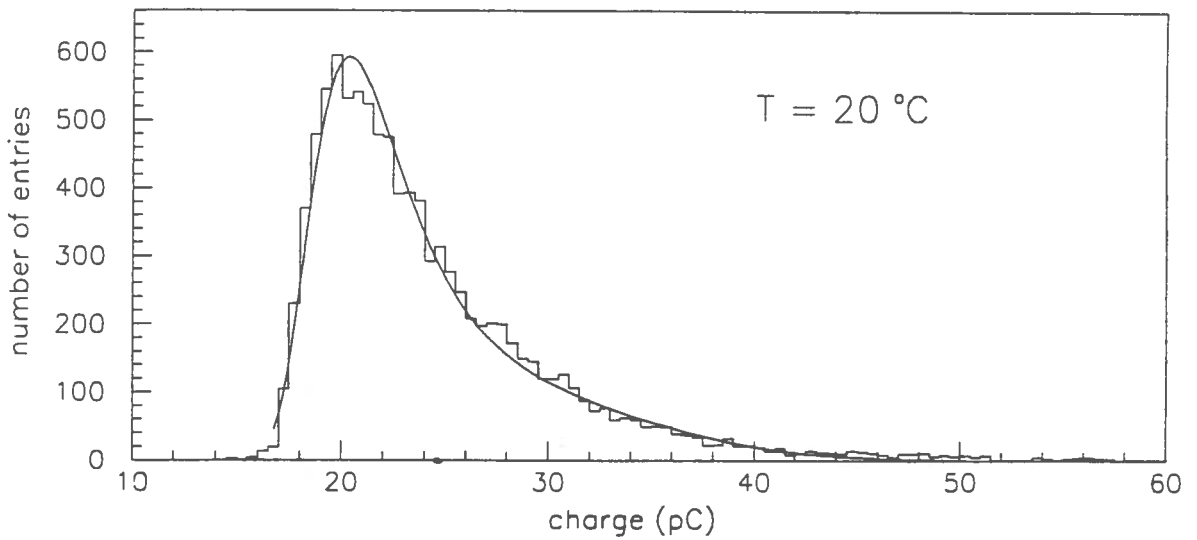
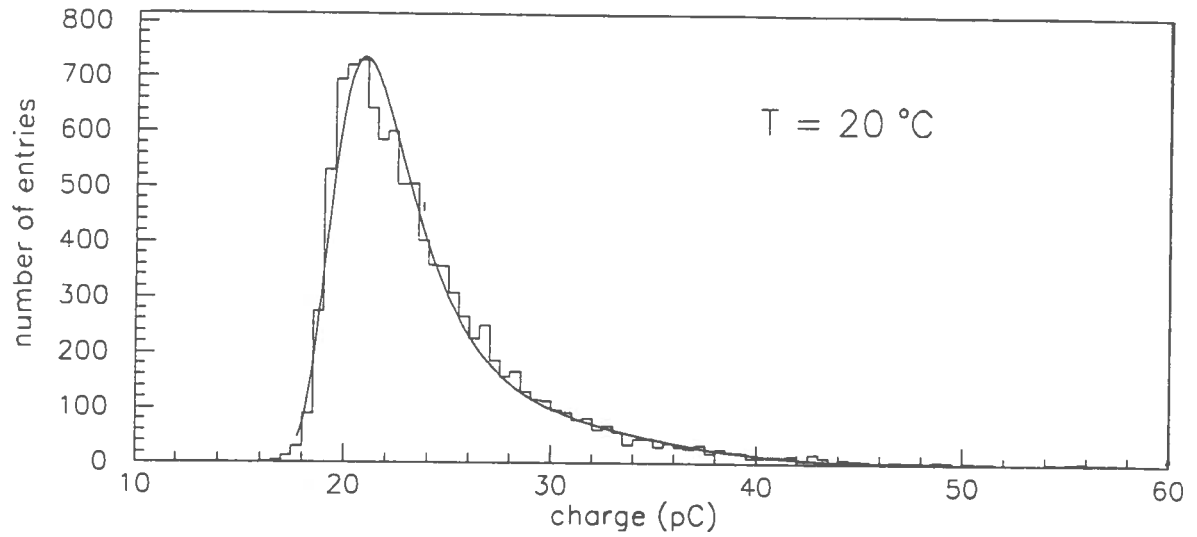


Fig. 2

Charge distribution measured in two strips of the silicon TOF telescope for 10000 electrons from the beta emitter ^{90}Sr . The fit to the data by a Landau curve is also shown. The curve at the top refers to the detector close to the source ^{90}Sr .

3. Temperature response of the electronic readout in various configurations.

The width of the TOF distribution of our silicon telescope is expected to be dominated by the electronic noise of the input bipolar transistor of the preamplifier and by the intrinsic time spread of the discriminator for signals close to the discriminator threshold. Many other minor contributions are also known. The electronic readout of one arm of the telescope is formed by the preamplifier, the insertion amplifier, the discriminator and the TDC. In order to disentangle the relative amounts of the noise sources as a function of the temperature, we have measured the noise of the electronic readout in three significant experimental configurations: (I) with silicon detectors disconnected from the preamplifier; (II) with silicon detectors connected to the amplifiers but not biased (turned-off detector) and (III) with silicon detectors connected and biased.

In configuration I the output of the insertion amplifier is connected to an ADC, LeCroy 2249A, having 0.25 pC charge bin gated with a constant gate of 50 ns. The input of the preamplifier is open. In this configuration, the discriminator and the TDC are removed from the electronic readout. The output noise level for the configuration I is shown in fig.3 and amounts to 1.18 pC (rms) at 20°C and 0.68 pC (rms) at -50°C.

Experimental data are compared with the expected noise level of this configuration through the relationship [10]:

$$i_{\text{tot}}^2 = i_p^2 + v_s^2/Z_T^2 \quad (1)$$

where i_p is the parallel current noise generated by the shot noise of the collector current and the base current of the bipolar transistor, v_s is the serial voltage noise generator of the thermal noise of the base spread resistance r_{bb} , and Z_T is the impedance resulting from the parallel of the base-emitter resistor (equal to $1/g$, where g is the transconductance) and the impedance of the base emitter capacitance.

In configuration II the measurements were repeated by connecting the silicon detector with no polarization . The effect of connecting a turned-off detector gives rise to a large stray capacitance at the input of the preamplifier . The other conditions of the measurement were unchanged. A relative increase, from 4% to 9%, of the noise at increasing temperature is observed (Fig.3 dotted line). Finally, in configuration III, the silicon detector was powered and the noise measurement was repeated.

In this configuration III the noise level approximately equals that observed in configuration I. In fact, the biasing resistor (100 MΩ) noise, the leakage current and capacitance of the detector, which are added in configuration III with respect to II, give a negligible contribution to the total noise level. The calculations, reported as dashed line in Fig.3, agrees with the experimental data. The slope is rather insensitive to the transistor type as long as the temperature dependence of the collector and base currents are calculated according to a model which has a very weak dependence on the specific bipolar transistor used.

The major source of the preamplifier noise is the shot noise of the first transistor stage which is calculated by the formula [11]:

$$i_p^2 = 2e \left(I_b + \frac{I_c}{\beta^2} \right)$$

where I_c is the collector current, I_b is the base current of the first stage, β is the dc amplification factor, e is the electron charge and i_p^2 is the mean value of the square current noise per unit frequency. The temperature dependence of the collector current is [12]:

$$\frac{\Delta I_c}{I_{c1}} = \frac{\Delta I_{co} \beta_1}{I_c} - \frac{\Delta V_{be}}{R_c I_c} + \frac{\Delta \beta}{\beta_1}$$

where ΔI_c is the collector current variation between two given temperatures T_1 and T_2 , I_{c1} is the collector current at temperature T_1 , R_c is the collector resistance ΔI_{co} is the current variation between the two given temperatures of the reverse saturation current, ΔV_{be} is the base emitter potential variation between the two temperatures, β_1 and $\Delta \beta$ are respectively the values of the current gain of the transistor at the temperature T_1 and the value of the current gain variation between these two temperatures. The variations of I_b are calculated by use of the relationship: $I_b = I_c / \beta$ where I_c and β are calculated at various temperatures.

We have also investigated the width of the pedestal, both as a function of the gate width entering the ADC and of the temperature of the preamplifier and the insertion amplifier. The results of these measurements are shown in Fig.4. The noise dependence versus gate width at a

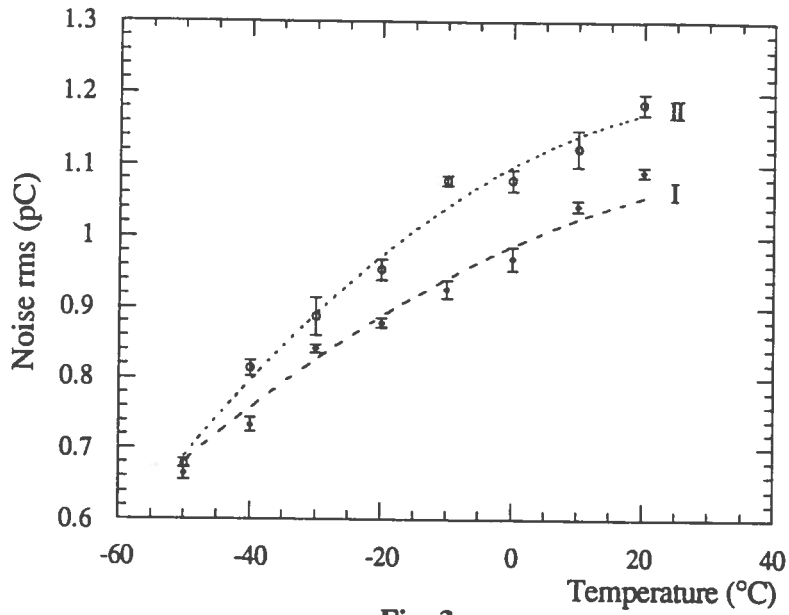


Fig. 3

Electronic noise (rms) of the readout versus temperature at the constant gate width of 50 ns. Solid and open circles correspond, respectively, to the configurations I and II described in the text. The dashed curves is calculated from equation (1) while the dotted curve is a only fit through the data.

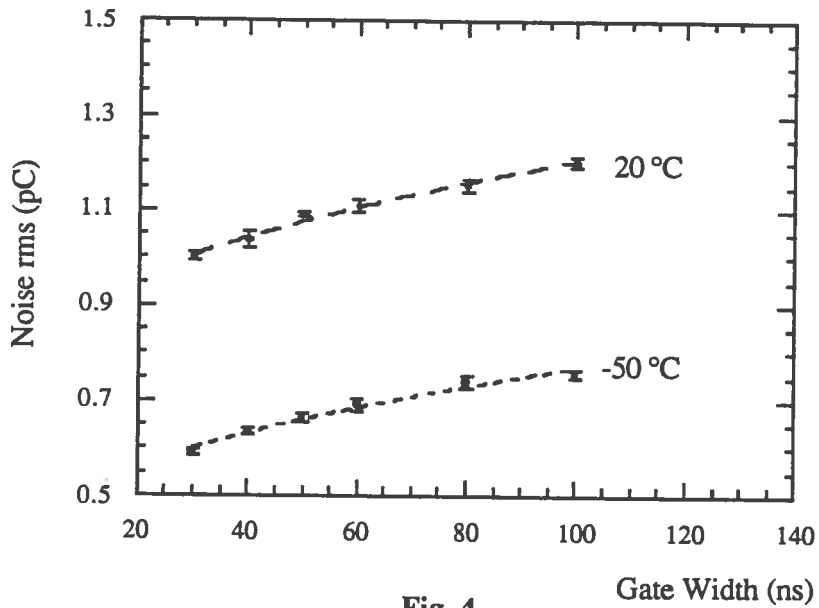


Fig. 4

Noise (rms) versus gate width (ADC) for various temperatures.

given temperature is fitted by the function $y = a + b\sqrt{t}$ where y is the output noise and t is the gate width; the constant b is dominated by the white noise of the input transistor of the preamplifier. At low gates (≈ 10 ns) the measurement is no longer reliable presumably because the bandwidth of the input stages of the ADC is not sufficient to integrate the charge signal. Presumably, a fraction of this pedestal noise is present on the leading edge of the preamplifier output which strongly affects the time resolution.

4. Noise level on the leading edge of the detector signal.

Measuring the noise on the leading edge of the preamplifier output signal is extremely important in a time-of-flight electronic readout, because this noise affects directly the time resolution of the telescope. By replacing the detector current signal by means of a charge pulse source, where the slew-rate is under control, is possible to evaluate the noise component on the detector pulse leading edge. The electronic chain for this measurement consists of a pulse generator, a preamplifier, a leading edge discriminator (LeCroy 821) and a TDC. In order to measure the electronic noise σ_N on the leading edge of the amplifier output pulse, we take advantage of the relationship [13]:

$$\sigma_T = \sigma_N \frac{dt}{dV} + \Delta t \quad (2)$$

where σ_T is the measured time resolution in the preamplifier discriminator chain and dt/dV is the inverse slew-rate of the output signal at the discriminator threshold. The constant term Δt is due to fluctuation of the transit time of the electronic chain, independent on the slew-rate of the discriminator output signal. We used the pulse generator Tektronix PG2012 with adjustable rise time from 200 ps up to 8000 ps. The results are shown in fig. 5. The value of σ_N is determined by a fit on measured values of the dt/dV at the output of the amplifier and by the time resolution σ_T . The contribution of Δt to the time resolution σ_T is negligible because its value, determined by the fit, is always minor than its error. It can be noticed that the decrement of the noise with varying temperature can be fitted with the same curve calculated theoretically with the method described in section 3. The importance of this measurement relies also on the fact that once the two parameters σ_N and Δt are known at a certain temperature and the average inverse slew-rate of the pulse coming from a particle crossing the detector is measured, it is possible to estimate from relationship (2) the time resolution for the time-of-flight spectrometer.

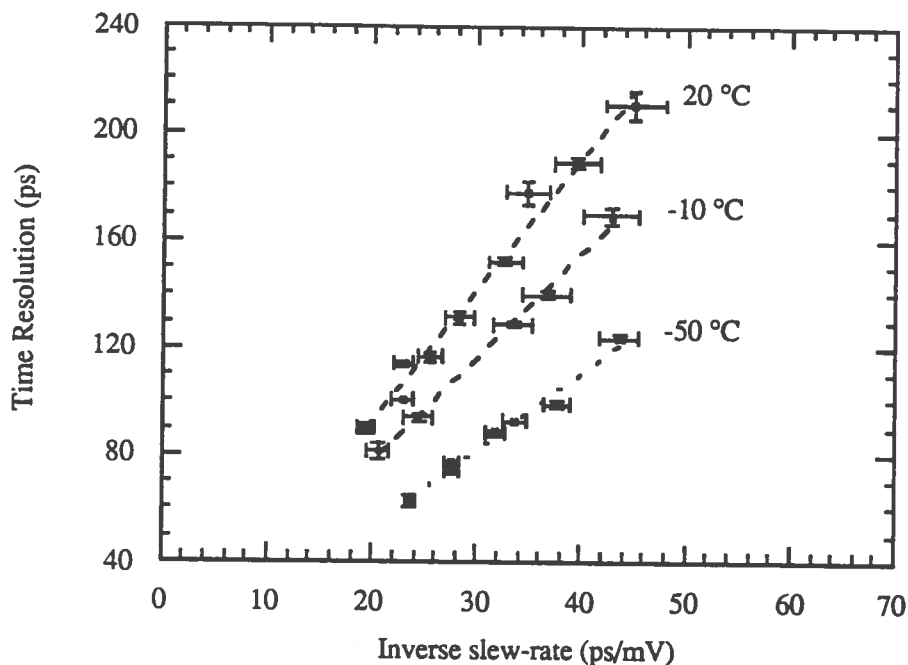


Fig. 5

Time resolution versus inverse slew-rate for the temperatures 20°C, -10°C and -50°C obtained by a pulse source. The slope of the straight line gives the voltage noise of the preamplifier at specified temperature

5. Time resolution of the telescope.

Two silicon detectors were connected to the electronic readout to measure time-of-flight resolution of one arm of the telescope. The electron source, ^{90}Sr , generates the detector signals. The typical time-of-flight distribution for electrons crossing the telescope is shown in fig.7. The data are interpolated by a normal distribution and its standard deviation is taken as measurement error. The TOF measurements have been repeated for several temperatures: 20, 10, 0, -10, -20, -30, -40 and -55 °C. Each data point is made of 10,000 events divided in 5 groups of 2000 events. The results of these measurements are summarized in fig.8. Only statistical errors are given. Systematic errors include the effect of integral non linearity of the TDC, the long term stability of the temperature ± 1 °C (known with a precision of 0.1 °C) and temperature instabilities of the electronic readout modules (CFD, TDC) outside the climatic chamber.

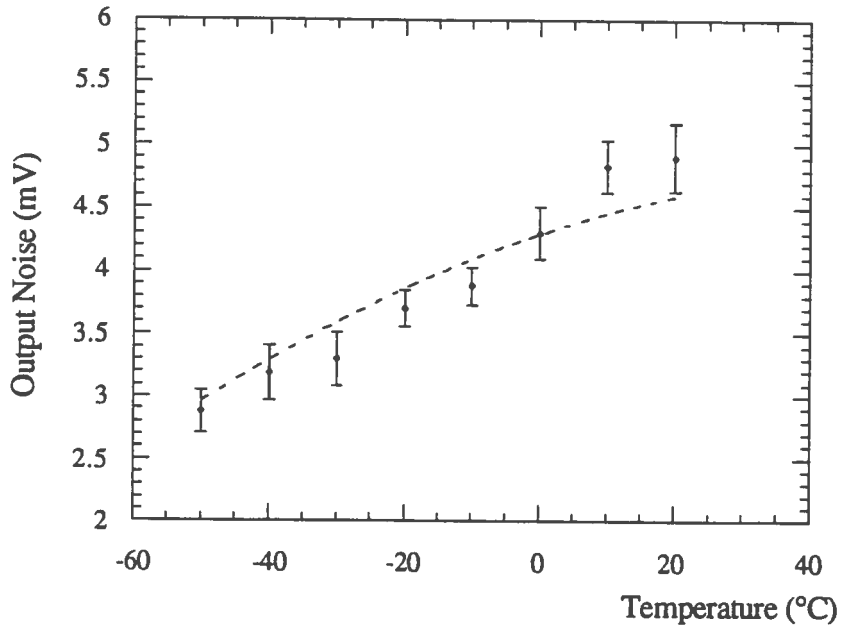


Fig. 6

Output voltage noise versus temperature. The fit is obtained by the equation (1) described in the text.

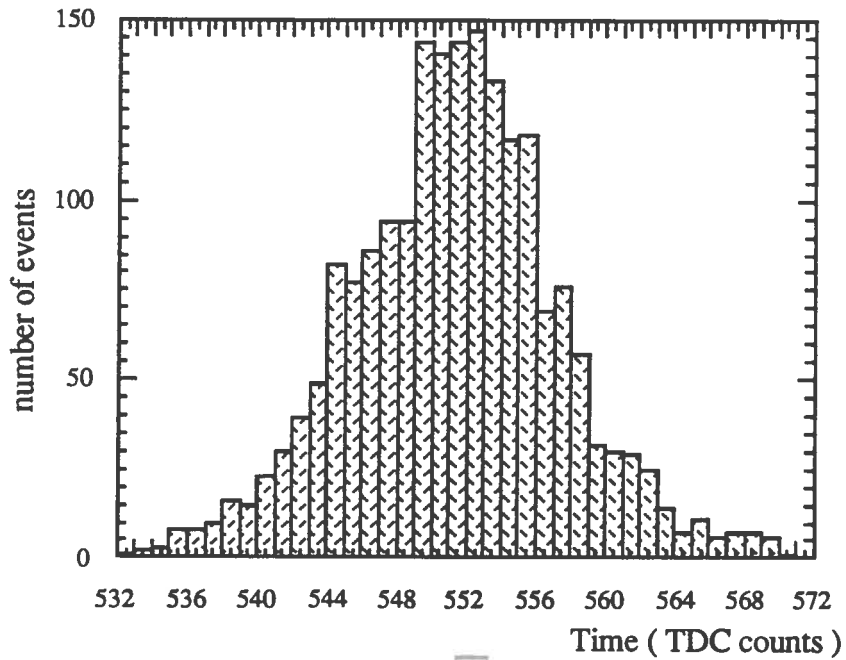


Fig. 7

Typical time-of-flight distribution between two silicon strips of thickness 250 μm at the temperature of -20 $^{\circ}\text{C}$ (a TDC count equals 24 ps).

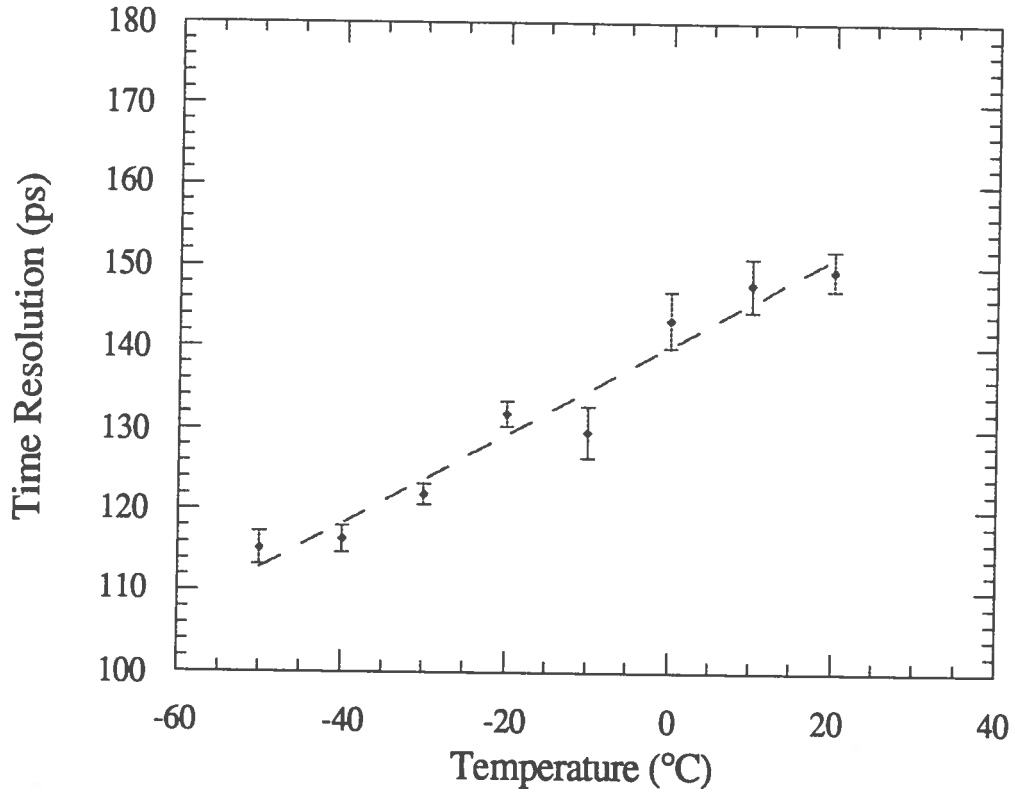


Fig. 8

Overall time resolution (rms) of the telescope versus temperature obtained by beta emitter ^{90}Sr . The dashed curve is a straight line fit to the data.

6. Conclusions.

We have studied a time-of-flight silicon strip telescope and its electronic readout as a function of the temperature between 20 °C and -50 °C. The detector and the readout have been subdivided into several useful segments in order to assess the influence of each segment on the overall time resolution of the instrument. Some of the experimental observations may be summed up as follows:

(A) The improvement of the TOF resolution of the telescope as the temperature decreases. It goes from 150 ps at 20 °C to 115 ps at -55°C.

This has to be ascribed to: (1) a decrease of the detector leakage current and the related shot noise; (2) a decrease of the thermal noise of the amplifier; (3) an increase of the mobility of the charge carriers that causes a reduction in the rise time of the pulse from the amplifier.

(B) The agreement between the measured noise level and the computed noise in several significant experimental configurations as shown in figs.3 and 6.

(C) The functional form describing the TOF resolution versus temperature is not unambiguous due to the large error bars in the measurement (see fig. 8). It is known that the shot noise of the bipolar transistor at the first stage of the preamplifier dominates the noise of the signal processing chain. Accordingly, more precise measurements of the TOF resolutions versus temperature might result in a closer connection with the curve (See fig.6) giving the shot noise of the collector current of the bipolar transistor versus temperature.

The upgrading of the present telescope for the improvement of the time resolution aims at the construction of a new preamplifier with low input impedance $\approx 30 \Omega$ and wide bandwidth ≈ 500 MHz resulting in higher slew-rate of the preamplifier output pulse. A further possibility is expected by the correction of the time-walk of the discriminator input pulse.

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