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SILICON DETECTORS IN CALORIMETRY (*)

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ABSTRACT

In electromagnetic calorimetry large-size silicon detectors, employing relative low-resistivity material (and, therefore, inexpensive), can be applied. The energy scale is defined by calibrating the detector with single non-showering relativistic particles. In this experiment the response of a large-area detector and its associated, especially developed, electronics to the energy-loss of single relativistic particles was tested. The electronics is able to calibrate and work in showering conditions. The standard deviation of the Gaussian noise contribution, which included the effect of the detector leakage current, capacitance, charge collection, and cabling, was 99.3 ± 5.3 keV. The energy resolution performance of the electronics, versus the equivalent detector capacitance (180 to 2000 pF), was found to be good. A silicon sandwiched calorimeter is expected to have good energy resolution compared to the conventional sandwiched calorimeters.

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1. - INTRODUCTION

Large-size silicon detectors employing relatively low-resistivity material (and thus inexpensive) can be applied in electromagnetic calorimetry. They are particularly adequate for experiments with geometric constraints(1), strong magnetic environment and relatively high counting rate(2). Their associated electronics can be accomodated nearby.

In high-energy physics experiments silicon detectors have been employed to detect relativistic particles. Unlike calorimetry applications(3) where a large number of devices, each with a large active area, is required, only a limited number of small detectors have been used.

High-resistivity large-size silicon wafers are expensive. But since in calorimetry the number of particles to be detected is quite large, a small depleted volume is sufficient and, therefore, relatively low-resistivity silicon detectors can be used. Inexpensive devices with relatively low resistivity silicon (1000-1500 Ωcm), low bias voltage (50-60 V) and of standard thickness (250-300 μm) can be produced. These silicon detectors, being of large area (20-30 cm^2) and not fully depleted, have high capacitances.

In this paper the response of a large area detector and its associated especially developed, electronics to the energy-loss of single relativistic hadrons was tested. The standard deviation of the Gaussian noise contribution which included high leakage current, capacitance, charge collection, and cabling was found. Also the energy resolution performance of the electronics versus the equivalent detector capacitance is shown.

2. - LOW-RESISTIVITY SILICON DETECTORS

As well known, silicon detectors are operated in reverse-biased condition. The applied bias-voltage assists the built-in voltage in removing free charges from the junction interface and the adjacent ions. The created charge depletion layer, in which the free carrier concentrations are below their thermal equilibrium values, provides the conditions for counter operation. The electrons and holes, created subsequently to the energy loss process, migrate towards the respective electrodes.

For relatively inexpensive low-resistivity (1000-1500 Ωcm) silicon detectors with a standard thickness of 300 μm and operated at a reverse bias of 60 V, the depleted region varies between 130 and 160 μm, the capacitance between 90 and 73 pF/cm^2, and the transit time between 5.6 and 8.0 nsec. The actual charge depletion thickness is slightly wider, because of charge diffused from the field-free region. The upper limit of charge migration towards the depletion region can be estimated by neglecting the recombination and considering only the charge diffusion.

In a field-free zone the diffusion equation for holes (minority carriers in an n-type silicon) is

$$\partial p'/\partial t = - p'/\tau_p + D_p \nabla^2 p' \tag{1}$$

where p' is the excess hole concentration to thermal equilibrium, τ_p is the hole lifetime, D_p is the hole diffusion coefficient. The solution of eq. (1) provides the transient of the hole excess in a unit-volume at a distance r from the position where P_o charges were created at t = 0

$$p'(t,r)dV = P_o \exp(-t/\tau_p) \exp(-r^2/4D_p t)/\left[8(\pi D_p t)^{3/2}\right] r^2 dr\, d\Omega$$

where Ω is the solid angle. For the integration time of the charge from the detector $\tau < \tau_p$, this equation becomes

$$p'(\tau,r)dV = P_o \left[\exp(-r^2/2\sigma^2)/\ (2\pi)^{3/2}\sigma^3\right] r^2 dr\, d\Omega \tag{2}$$

where $\sigma = \sqrt{(2D_p\ )}$.

From eq. (2) the probability of a charge created at a distance r from the depletion region to diffuse into it can be calculated. It can be shown that charge created up to distance σ from the depletion region may migrate into it. Also the total amount of charge is found to be $1/3\, \sigma N$, where N is the number of electron-hole pairs created per unit length and is assumed to be constant over σ. For an integration time of about 25 nsec (namely about three times the transit time for an undepleted detector with 1500 Ωcm resistivity), only an equivalent region smaller than 8 μm contributes to the sensitive thickness of the detector, when the electron migration towards the electrode is taken into account.

The performance of a high-resistivity silicon detector operated fully and partially depleted was investigated by using a 30 GeV/c pion beam at the CERN-SPS(4). At any bias voltage lower than that required for full depletion, the resulting sensed energy-straggling spectrum was in agreement with the energy-loss distribution(5) of a relativistic particle traversing a silicon absorber of thickness equal to the actual depleted layer.

3. - ELECTRONICS FOR HIGH-CAPACITANCE SILICON DETECTORS

A preamplifier (Fig. 1) capable of working with detectors of up to 2600 pF capacitances, was developed. The output signals of the preamplifier are fed into an Amplifying and Shaping Stage, ASS (Fig. 2) which was designed to give optimal results. The preamplifier is a relatively low-cost High Capacitance oriented Charge sensitive Preamplifier (HCCP) which delivers a voltage output for a time-varying coulomb charge at its input. Its main purpose is to reduce the capacitance effect of not fully depleted silicon detectors. The dynamic range of 1000 is derived from the requirement of one to 1000 particles per event. The required test pulse amplitudes were calculated from $E_{eq} = V_T C_T E_c q^{-1}$ where E_{eq} is the average energy loss, V_T is the

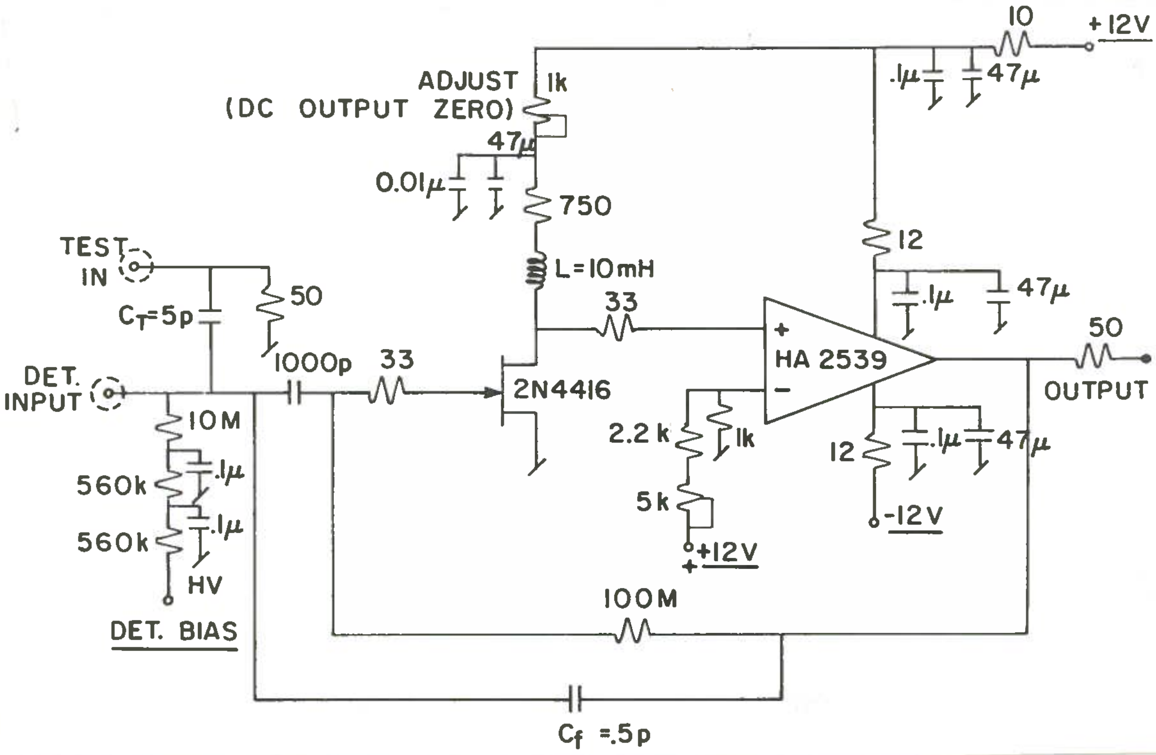

FIG. 1 - Charge sensitive preamplifier.

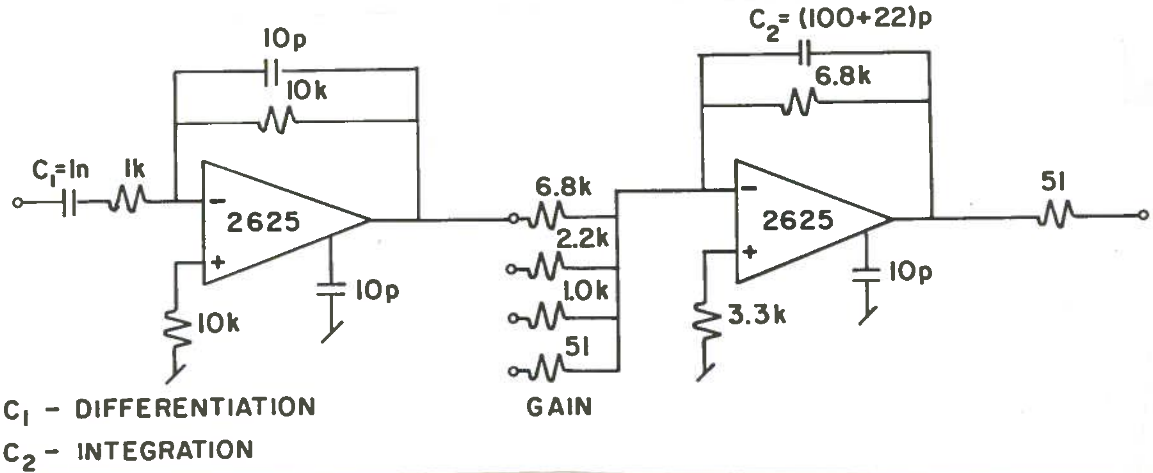

FIG. 2 - Shaping and amplifying stage.

test pulse, C_T is the test capacitance and the stray capacitance, E_c is the conversion energy of silicon, and q is the electron charge. For E_{eq} = 50 keV, C_T = 5 pF, E_c = = 3.6 eV and q = 1.6×10^{-19} Cb and one particle per event is V_T = 0.44 mV.

4. - EXPERIMENTAL SET-UP

The experiment was carried out in the X7 beam of the CERN SPS. The energy of the incoming proton beam was 100 GeV and the intensity roughly 10^3 particles per burst (2 sec).

One scintillator of 5×5 mm^2, both its lateral sides being coupled (without light guides) each to a photomultiplier, is located 10 cm upstream of the silicon detector and provides the geometrical definition of the beam. The coincidence of the shaped signals coming from the two photomultipliers gives the trigger. The pulse coming from the solid-state detector is sent to the HCCP preamplifier and subsequently to the ASS shaper which provides an output signal, with about 1.7 μsec risetime and about 4 μsec base-time, which is recorded by a LeCroy 2259 peak sensing ADC. The distance between the experimental area and the counting room was about 90 m. The trigger signal generates a 1.8 μsec gate to the ADC. The 5×5 cm^2, 335 μm thick detector (Fig. 3) was depleted to 295 μm. Its capacitance was estimated to be about

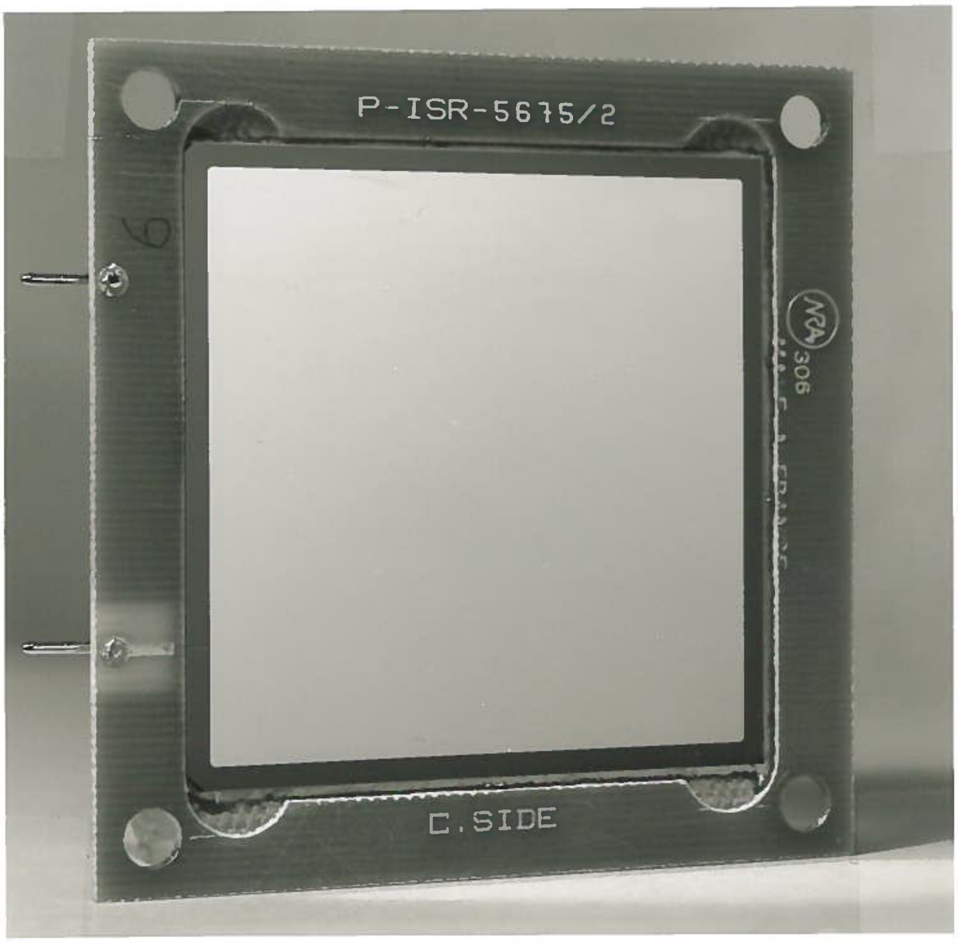

FIG. 3 - Silicon detector of 5×5 cm^2 active area.

1000 pF. The leakage current varied between 15 and 25 μA but despite the low-cost oriented manufacturing of the detectors it seems that they would be considerably improved in the future.

5. - EXPERIMENTAL RESULTS AND DISCUSSION

In calorimetry the energy scale is defined by calibrating the detector with single non-showering relativistic particles (usually muons). The purpose of the experiment was to test the response of a large area detector and its associated especially developed electronics, to the energy-loss of single relativistic hadrons.

We believe that it is important to both be able to calibrate and work in showering conditions, therefore, the electronics was developed accordingly.

Fig. 4 shows the energy-straggling spectrum sensed by the silicon detector. The full line represents the fit to the experimental data, which are well described by the energy-loss distribution(1, 5) once the gaussian noise contribution is subtracted. The standard deviation of the gaussian noise contribution was 99.3 ± 5.3 keV. It included the effect of the detector high leakage current, capacitance, charge collection, and cabling.

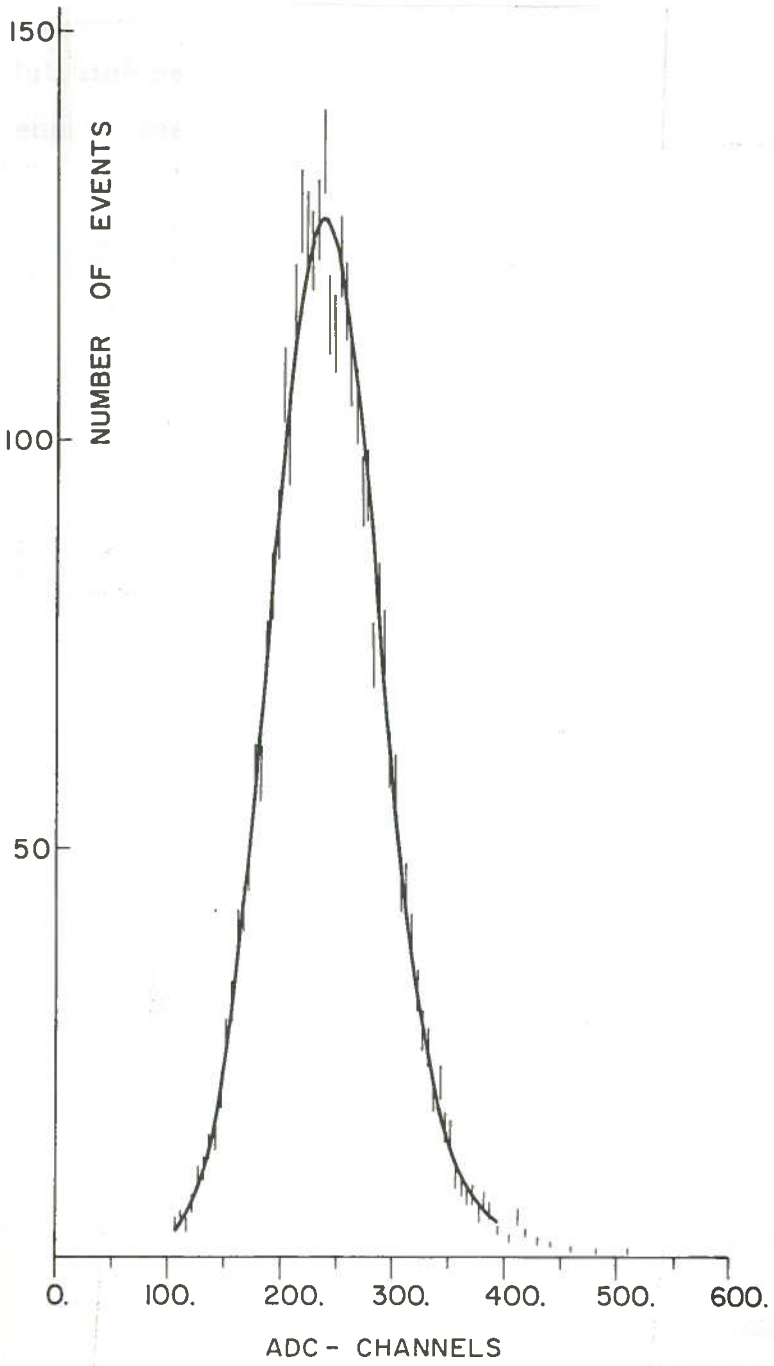

FIG. 4 - Energy-loss of 100 GeV protons traversing a 5×5 cm^2 silicon detector. The detector was depleted to 295 μm and the peak position was about 84.5 keV. The zero energy was at the ADC chanel number 189.

Both the HCCP preamplifier and ASS shaper were tested with the detector replaced by a wide range of capacitors and the ADC-channel scale calibrated by the most probable energy loss of the 100 GeV/c protons. The peak position of the energy-straggling spectrum, namely 84.5 keV, was found to be at the 39 ADC-channel from the zero energy.

In Fig. 5 the energy resolution performance of the electronics versus the equivalent detector capacitance is shown. It is a straight line as expected and the energy resolution is good.

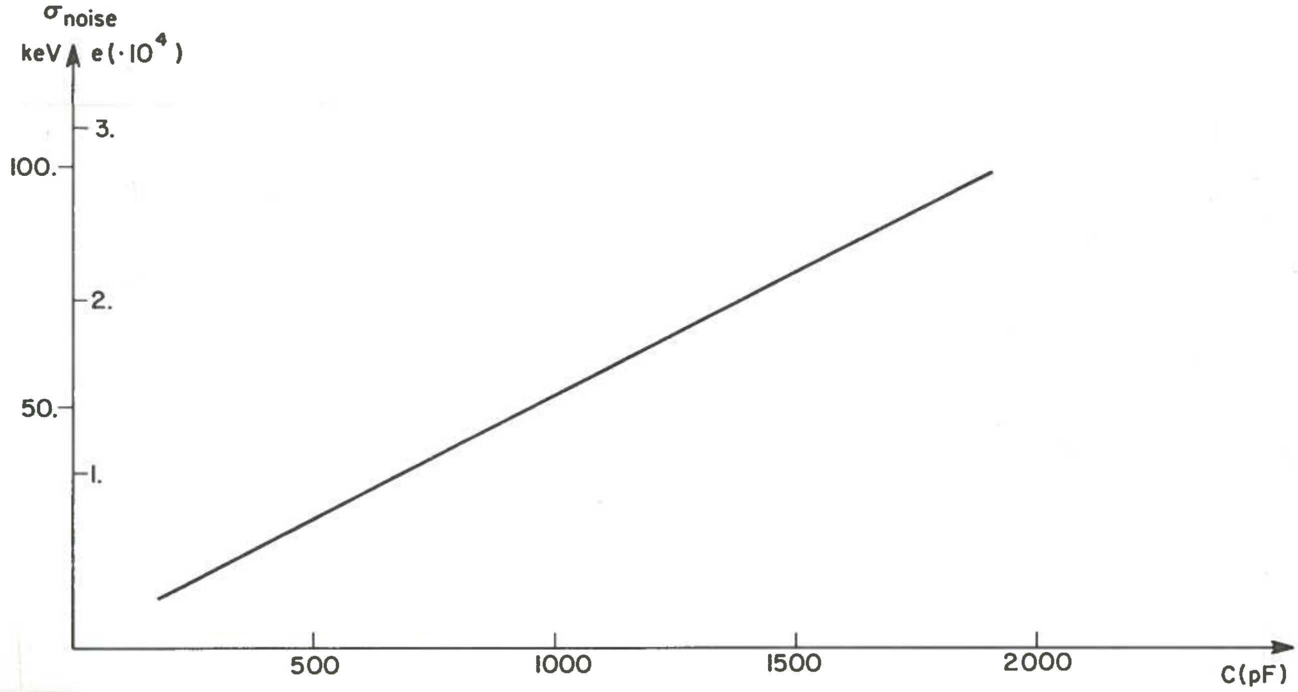

FIG. 5 - The standard deviation of the gaussian noise distribution versus input capacitance.

High capacitance silicon detectors, by properly operating them, can be calibrated with single relativistic particles, which provide the energy scale for a silicon sandwiched electromagnetic calorimeter(3). This calorimeter is expected to have a particularly good energy resolution compared to the conventional sandwiched calorimeters.

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