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**Experimental results from a sandwich calorimeter using U-absorbers and
0.25m² of Si active area**

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Abstract:

The electromagnetic section of a full hadronic calorimeter, using uranium absorbers of 0.25m² of silicon active area, were investigated.

The overall performance of the large amount of silicon detectors and especially developed associated electronics, seems to be stable and reliable.

During a four-weeks run at the t_s, CERN-PS electron beam of 2 to 6 GeV, no variation of energy calibration of the calorimeter was observed.

The energy resolution for electromagnetic showers was found to be about 19.8% $\sqrt{(\tau/E)}$ for a calorimeter depth of 15.6 X₀ (radiation lengths), with Si-samplers depleted to 200μm.

A reduction of energy response to electromagnetic showers, can be exploited to equalize the response of a Si/U hadronic calorimeter to incoming electrons and hadrons.

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1. Introduction

Investigations of the usage of large ion-implanted silicon detectors in high-energy physics, especially in calorimetry, have been started lately [1]. Studies on not fully depleted detectors were also performed recently, in order to find out the applicability of relatively inexpensive, low-resistivity silicon detectors [2] - [5].

The SICAPO (Silicon CALorimeter and POLarimeter) Collaboration (Genoa, Florence, Hamburg, McGill-Montreal, Milan, Tel-Aviv and Trieste) is planning to develop at CERN, a full Si/U hadronic calorimeter, with 130 silicon sampling plates (about 6.5 m²) made of mosaic modules, located after each 5mm of uranium (4.8% of an interaction length). Since 1983, at the CERN-PS and SPS, SICAPO has carried out preliminary experimental tests on Si/W and Si/U sandwich calorimeters and on silicon detectors, both fully depleted.

In this paper, the electromagnetic section of a full hadronic calorimeter using uranium absorbers and about 0.25m² of silicon active area, was investigated.

For a calorimeter depth of 15.6 X₀ (radiation lengths) and silicon samplers depleted to 200μm, the energy resolution for electromagnetic showers was about 19.8% ($\sqrt{\tau}/E$).

The silicon mosaics consisted of about 90 Si-detectors of 28cm² each. The test was performed with 5 silicon detectors, each of 28cm² (a total area of 0.25m²) connected in series, employing fast electronics, in order to demonstrate the feasibility of the future 6.5m² Si-calorimeter and also to study the hadron compensating calorimeter.

2. Silicon mosaic and readout electronics

2.1. Silicon-sampling unit

A silicon-sampling unit of 504cm² active area) is a mosaic made of 18 trapezoidal silicon detectors (28cm² area and 400μm thick each). The trapezoidal detectors (p-i-n diodes) were processed from 100mm diameter silicon wafers and operated at a depleted layer width of 200μm. A laser-cutting method was developed using a CO₂ laser. Floating zone silicon, with typical resistivity of 1 - 2kΩcm, seems to be suitable for large-area detectors in calorimetric applications.

The active area of a silicon detector is extended laterally, beyond the junction region, (A_j), by electrical field lines. The extended active area

(A_E) is, to first approximation, proportional to the depleted region with (X_d):

$$A_E = \lambda X_d P \text{ [cm}^2\text{]}$$

where P is the junction perimeter and λ (its fitted value was found to be 0.10 ± 0.06 [1]) is the ratio between the lateral extension of the active area and X_d . Thus, the total active area of a device is given by the sum of A_j and A_E .

By assembling a silicon detector mosaic, dead areas are necessarily created, since the supporting wafer is larger than the junction region. In order to minimize losses in the active area, the layer cut should be performed very close to the junction edge. With this technique, a negligible variation of leakage current occurs, when the cut is made as close as $175 \mu\text{m}$ to the metallized region of the detector[1]. The mosaic dead area can thus be reduced to a few percent of the total active area.

Relatively low resistivity material detectors are expected to perform better than high resistivity ones [6] and can be used not fully depleted. With the same space charge region width, their performance is the same as that of fully depleted detectors [7].

For detector modules, two sheets of fiberglass were used to bring the electrical connections to both the junction and the rear side of the detectors, by means of silicon rubber (to the fiberglass) and conductive epoxy resin (to the metal paths). The contacts were brought to an external flat cable.

The calibration of the energy was performed by using an α -source and recording the ADC value of its signal. Radioactive α -sources (usually U^{233}) can be deposited on the detector surface by a technique, similar to sputtering, and provides in-situ calibration of silicon detectors placed in experimental apparatus.

3. Readout electronics and leakage current monitoring system

In order to reduce the number of electronic channels and the overall detector capacitance, a serial coupling of silicon devices (Fig.1) has been studied.

Along the beam direction, five successive sampling mosaics were connected to a readout unit (Fig.2). The serial connection consists of five not fully depleted silicon detectors, therefore, their capacitance is high but can be changed easily by changing the bias. Also the charge response can be adjusted easily.

The silicon detectors of a sampling plane require the same bias voltage,

in order to be depleted at 200 μm . Due to the serial coupling, the overall capacitance of the five 28 cm^2 depletion width is about 290 pF.

It can be shown that the stray capacitance between the silicon detector and the absorber causes that the responses of the five detectors of a single readout unit are not identical. This problem can be solved by slightly adjusting each detector capacitance, i.e., the depleted layer width. In the present set-up (8 mm spacing between two uranium plates), the adjustment is for the worst case (the detector connected directly to the preamplifier) of about 2.5%. It is being performed by modifying by the same measure of depleted layer widths. In order to provide easy compensation, even for smaller spacings between absorber planes, a new version of the preamplifier, with floating balanced input, is being studied. The new preamplifier is expected to require one fifth detector capacitance variation than the present one.

A hybrid network circuit realizes the serial coupling of detectors located at the same position in the five mosaic planes and provides the output connections for the leakage current monitoring system. By measuring the voltage across a resistor in series with each detector, the leakage current is monitored. A multiplexing system is able to scan through one channel up to about 2000 measuring points (detectors). The resolution of the system is 100 nA and the full scale range is 25.5 μA . The conversion is realized by an ADC (Analog to Digital Converter) of 8 bits.

The CPU-board consists of 6502 μ -processors. The program runs on two EPROMs of 8 kbytes each and two static CMOS RAMs of 8 kbytes each, to store the currents of the detectors.

Asynchronous communication adaptors are used to connect the system to an RS232 Video-terminal and a serial printer. On this terminal, through graphic representation, an updated picture of a plane and a particular detector being measured are presented, including the currents of the detectors of a plane, by addressing a particular plane. The acquisition can be set to "synchronized" or to "random". A function can be selected to calibrate the ADC.

For fast electronics, (shaping time of about 20 ns) the output signal is proportional to the number of electron-hole pairs, generated in the space-charge region. A long integrating time of the associated electronics provides a signal with a contribution, due to charge which migrates from the field-free region. This charge corresponds to the collection of electron-hole pairs generated in 25 to 50 μm inside the field-free zone for collection time of about 0.5 to 1.0 μs [3].

A charge-sensitive amplifier (Fig.3) was designed and built to give a linear response (dynamic range of about three and a half decades) for

energies up to 80-90 MeV. The rise-time of the output signals is about 25 ns and the fall-time is about 60 ns. The standard deviation of the Gaussian noise-distribution was found in a laboratory test to be about 15 keV for an input capacitance of 330 pF. This value takes into account both the overall detector capacitance and the stray capacitance.

When the detectors and readout electronics were positioned in the calorimeter, the Gaussian noise distribution was between 45 and 60 keV, taking into consideration the 60 m long cable and the amplifier.

The number of electron-hole pairs generated by a relativistic particle traversing a silicon detector, is large compared to the charge carriers of other devices, used as an active sampling layer in calorimetry. A depleted layer width of 150-300 μm , is sufficient to yield a good signal-to-noise ratio, even for a single non-showering particle, when proper electronics is used. Moreover, in the usual showering condition, many particles are traversing the active layer of the calorimeter.

In our case, for 2 GeV electrons, the signal-to-noise ratio was greater than 70. It can, therefore, be said that no limitations were observed because of signal reduction caused by the parasitic capacitance between detectors and absorbers [8].

4. Experimental set-up and results

4.1. The experimental set-up

The electromagnetic section of the SICAPO Si/U hadronic calorimeter contained $15.6 X_0$ (radiation lengths) of uranium. The silicon mosaics were located next to a 5 mm thick ($1.56 X_0$) and $50 \times 50 \text{ cm}^2$ area uranium plate. Two readout units for the full calorimeter were required by the silicon mosaics (Fig.4). At $3.1 X_0$ a mosaic of 21 fully depleted detectors of 1 cm^2 area was located. At $10.9 X_0$ two mosaics (one of 21 fully depleted detectors of 1 cm^2 area and one of 11 trapezoidal detectors of 28 cm^2 area) were located. These mosaics were used in the off-line analysis to check the lateral shower containment. The silicon detectors were depleted at $200 \mu\text{m}$ and the leakage currents were between 0.3 and $2.0 \mu\text{A}$. The total silicon active area was about 0.25 m^2 .

The test was performed in the t_9 beam at the CERN-PS with incoming electrons energies of 2, 4 and 6 GeV. A gas Cherenkov counter, filled with helium at 1.4 bar, was used to select electrons. A beam scanner, consisting of a scintillator counter of $0.5 \times 0.5 \text{ cm}^2$ area, ensured that only those electrons, impinging on the middle of the calorimeter, triggered. Before

and after each period of data taking, the calorimeter was calibrated and the electronics equalized, using an α -source. A pedestal run was taken before each data run.

4.2. Experimental results

Fig. 5 shows the mean energy deposited in the calorimeter, which is a linear function of the incoming electron energy

$$\epsilon = (3.56 \pm 0.14) E + (-0.18 \pm 0.41) \text{ [MeV]}$$

where E is given in GeV. The reduction of the energy response, compared to the one measured in [9], is mainly due to the two fiberglass supports, used to bring the electrical connection to both the junction and the rear side of the detectors and the three mosaics not used to readout the calorimeter sensed energy, but inserted like additional absorbers in front of the second and seventh mosaic of the calorimeter. The fiberglass absorbs soft electrons, thus reducing the total energy sensed. A low Z absorber can be used to reduce the response of the electromagnetic component in a hadronic shower, while the pure hadron (most of them relativistic or quasi-relativistic) component, is practically not affected. In this way $e/h = 1$ can be obtained, without exploiting the neutrons, generated in the nuclear collisions and subsequent break-up.

The energy resolution $[\sigma(E)/E]$ was found to be, to a first approximation [10], [11], by:

$$\sigma(E)/E = k\sqrt{\tau}/E$$

where τ is the number of radiation lengths of passive material interspaced between two active samplers. In Fig. 6 the measured values of k are shown; the weighted mean value of k is $(19.8 \pm 1.3)\%$. In a previous measurement [12], $k = (17.6 \pm 0.3)\%$ was found for a Si/W calorimeter, containing $24 X_0$. However, the longitudinal energy loss, affects the energy resolution. In Fig. 7 the parameter k (for incoming electron energy of 4 GeV) is shown for four values of the Si/W calorimeter total depths: 20, 22 and 24 X_0 . Thus, the actually found value of k is in agreement with that absorbed in the Si/W calorimeter [12].

5. Conclusions

A silicon-sampling calorimeter satisfies the requirements of compactness, granularity, long-time stability and reliability, necessary in colliding beam machine experiments.

The energy resolution of the tested calorimeter for electromagnetic showers is in good agreement with the expected value for a calorimeter, having a depth of about 16 radiation lengths (Fig. 7). This result was obtained by running a Si/U calorimeter, consisting of 0.25 m² of Si-detectors, serially coupled clusters of 5 detectors and fast electronics.

The energy sensed by the calorimeter is a linear function of the incoming electron's energy. The observed reduction of the energy sensed in the electromagnetic showers due to the fiberglass supports in front of the silicon mosaic, can be exploited to equalize the response of a Si/U hadronic calorimeter to incoming electrons and hadrons. The fine timing of the calorimeter energy response to the electromagnetic component allows to have $e/h = 1$ and $\sigma(E)/E$ proportional to $1/\sqrt{E}$.

Both the energy resolution and the energy response of the calorimeter were measured four times, over a running period of four weeks and the results were found to be in good agreement. The results confirm the reliability of a device employing large active area, not fully depleted silicon detectors.

The leakage current variation was found to be less than $\pm 5\%$.

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FIGURE CAPTIONS

Fig.1 : Serial coupling of five Si-detectors.

Fig.2 : Readout unit for five sampling mosaic planes. The flat cables on the left hand side, transfer signals from the mosaic planes. In the middle of the readout unit, there are 18 hybrid network circuits for the serial coupling of detectors and on the right hand side, the hybrid preamplifiers. The leakage current of the 90 detectors can be monitored via the output pins, next to the preamplifiers.

Fig.3 : Preamplifier

Fig.4 : Silicon plane and electronics (top part of the calorimeter container) used in the test of the electromagnetic section of Si/U SICAPO calorimeter.

Fig.5 : Mean energy deposited in the calorimeter as a function of the incoming electron energy.

Fig.6 : k values in % vs. incoming electron energy.

Fig.7 : k values in % for different total depths of Si/W calorimeter.

$R1 = 220K$
 $R2 = 100K$
 $R3 = 22K$
 $C1 = 10nF$
 $C2 = 100nF$
 $C3 = 100nF$
 $R4 = 10K$

Fig. 2

Fig.4

Fig 7