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SILICON DETECTORS USED FOR BEAM DIAGNOSTICS IN THE LEP COLLIDER

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Compact silicon-tungsten calorimeters are used in the LEP e^+e^- collider to monitor luminosity and particle background rates at the four interaction points and to measure the degree of transverse polarization of the circulating electron beam. The article describes the function and the technical realization of the different detectors and presents first operational experience as well as some physics results obtained.

1. Introduction

Large-area silicon detectors have been developed for calorimetry in the recent years [1]. The LEP instrumentation group has made use of this technology in order to monitor synchrotron radiation (SR) and electron and positron rates near the four interaction points (IP), as well as the beam interaction rates via the elastic Bhabha scattering reaction. The same technology is used for detecting the vertical asymmetry in the profiles of high-energy photons produced by Compton scattering of a polarized photon laser beam on the LEP electron beam.

Section 2 deals with the silicon detectors, associated electronics, data acquisition and slow control. Sections 3 and 4 are dedicated to the layouts, assemblies and results of the Bhabha monitors and of the polarimeter detector.

2. Hardware and data acquisition

2.1 The silicon detectors and their front-end electronics

Various unsegmented (pads) and strip silicon detectors are employed. Figure 1 shows the detectors and associated front-end electronics used in the Bhabha calorimeters. The pad detector has a size of $50 \times 50 \text{ mm}^2$ [2]. The strip detector area is $40 \times 40 \text{ mm}^2$ consisting of 16 strips: 8 strips with 1 mm pitch located at the side facing the

LEP beam, followed by 8 strips with 4 mm pitch [3]. In order to reduce the insensitive zone the silicon oxide surrounding the active silicon area is reduced to 0.5 mm on the side facing the beam.

FIGURE 1
Silicon detector planes (right) and associated front-end electronics for the Bhabha calorimeters.

Figure 2 shows the two strip planes [2] used for the polarimeter detector, each with 16 readout channels. The first detector, of area $40 \times 40 \text{ mm}^2$, is made from 40 strips of 1 mm width. The 16 readout channels are connected to two neighbouring strips bonded together and the two

times four outer strips are grounded. The second detector of area $50 \times 50 \text{ mm}^2$ has 16 strips of 3.1 mm width.

FIGURE 2
Silicon detector planes (right) and associated front end electronics for the polarimeter detector.

The ion implanted silicon detectors are $300 \mu\text{m}$ thick and are used fully depleted. They are glued with a conductive epoxy onto 0.52 mm thick ceramic plates. These plates have thick film-conductive lines onto which the pads and the strips are bonded. The desired operational bias of each detector has been determined by measuring its capacitance versus voltage characteristic and is applied on the ohmic side; it varies between 30 V and 55 V . The charge collection efficiency of the detectors has been tested with an alpha source (^{241}Am , 5.4 MeV). Typical diode reverse currents varied between $0.3 \mu\text{A}$ and $0.6 \mu\text{A}$ at room temperature.

The detectors are inserted between specially machined tungsten plates. The gap between two neighbouring plates is 1.3 mm . The alignment of the Si-W elements is ensured by 2 dowels inserted into calibrated holes of the ceramic supports and of the tungsten plates.

The front-end amplifiers, realized in Surface Mounted Device technology are current sensitive

and AC coupled to the detectors [4]. Their gains are adjustable from 100 to 1000 depending on the choice of feedback capacitors. A one-channel preamplifier (LAD3) for the silicon pads is constructed from integrated circuit LM 359M in bipolar technology. The silicon-strip amplifier (MSP16) has 16 channels using BF 992 FET transistors [5]. The preamplifier cards integrate the shapers and the bipolar line drivers. Figure 3 shows the measured equivalent noise output of the different preamplifiers versus the detector input capacitance. The output signals have 100 ns rise time with 300 ns FWHM and 20 ns with 70 ns FWHM for LAD3 and MSP16, respectively.

FIGURE 3
Equivalent noise output expressed in keV for preamplifiers as a function of detector input capacitance.

The detector radiation hardness was tested in the following way: two silicon detectors of 1 cm^2 surface have been irradiated by gamma rays of a ^{60}Co source (1.17 and 1.33 MeV). This energy is in the range of the critical energy of the SR produced in the superconductive quadrupoles close to the interacting points. The behaviour of their reverse currents is shown in fig. 4 as a function of the irradiation dose. For a dose of

10^6 Gy (which is much beyond the estimated dose the detectors will receive after several years in LEP) the increase of the measured reverse currents is less than a factor of ten, while the charge collection efficiency stays unchanged.

FIGURE 4
Diode reverse currents for 2 silicon pads of 1 cm^2 as a function of the irradiated dose induced by a ^{60}Co source.

2.2 Analog electronics

An overview of the analog electronics is shown in fig. 5.

The bipolar signals for the preamplifiers are transmitted through 60-80 m of twisted-pair cables and are converted into negative pulses by 16 channel-receiver Europe modules made of TL 592 integrated circuits.

These signals are connected to 16 channels of integrate and hold modules described in ref. [4]. They have been realized in Europe standard using the design described in ref. [6]. The input charge is integrated during an external gate (300 ns for strip detectors and 1000 ns for pads detectors) and stored on 620 pF capacitors. The integration sensitivity is 1.6 mV/pC with a maximum output amplitude of -1.5 V . The capacitors are discharged by an external fast clear signal whenever an event has been accepted and read or was rejected. The front-end of each module performs a fast analog sum of the 16 input charge pulses which can be used as an event trigger.

FIGURE 5 Analog electronics.

2.3 Data digitalization and acquisition

The flow-chart corresponding to this chapter is shown in fig. 6.

FIGURE 6 Data acquisition system.

The analog charges stored in the integrate and hold module are digitized in a CES 8160 module containing a 128-channel multiplexer and four 12-bit ADCs (AD 7672 KN03). They work in parallel with a digitizing time of 3 μ s. This module is controlled by the CES 8150 card which includes several parts:

- a 10 MHz DSP 56001 from Motorola;
- a DRAM accessible simultaneously by the VME bus and the DSP;
- a sequencer which is driven by an external trigger and sends instructions to the external data cards. At the end of the cycle, the data are stored in a 512-word FIFO. The sequencer can drive up to 8 external cards.

The FIFO is used as an intermediate buffer between the external data cards and the DSP. When the FIFO has received a block of data an interrupt is sent to the DSP which reads the data, performs the programmed data processing and stores the results in the DRAM.

The data stored in these memories are transferred to the local VME TMS 68010 micro-

processors for further analysis and are finally sent to the LEP control-room on request.

2.4 Slow control

The detectors and their local electronics can be controlled from standard LEP terminals which are connected via the LEP control system to the Equipment Control Assemblers (ECA). These contain the microprocessors and the following dedicated VME modules:

- a 16-channel bias module (BHA 160) applying maximum voltages of 70 V in steps of 0.3 V to the silicon detectors and measuring their diode reverse currents;
- a 4-channel programmable threshold discriminator module (CES DISC 8151) used for trigger purpose with an adjustable level from 10 to 1000 mV in steps of 10 mV;
- a 96-channel I/O module (ICV 196) providing the desired trigger selection (event selection, bunch selection), and the acquisition time period;
- a 16-channel programmable delay module (PDM) providing the various time sequences needed in synchronism with bunch passages.

3. Interaction rate and background monitors

The Bhabha detectors must provide high counting rates in order to be useful for luminosity and background optimization during the LEP operation. As the Bhabha cross section decreases with the third power of the Bhabha scattering angle the monitors must be brought as close to the circulating beams as possible. They should equally work for the various optical configurations used in LEP.

3.1 Monitor layout and acceptances

A detailed description of the monitor design is given in refs [7, 8]. The layout of an interaction region, including the interaction rate monitors is shown in fig. 7. Four calorimeters forming two

FIGURE 7 Bhabha monitor layout around a LEP interaction point.

independent monitors are incorporated into the mobile jaws of the horizontal collimators, symmetrically located at 15 m from the interacting points. The trajectories of elastically scattered (e^+e^-) pairs are indicated for the back-up ($\beta_y^* = 20$ cm) and for the low-beta optics ($\beta_y^* = 7$ cm). The movable collimator jaws are adjusted as close to the circulating LEP beams as the photon background at the experiments or beam lifetime allows. When closed to ten standard deviations of the horizontal beam width, the monitors intercept Bhabha electrons and positrons down to scattering angles of 2 mrad.

The counted Bhabha rate is the product of the luminosity times the integral σ_D of the differential Bhabha cross section over the detector acceptance. The cross section itself is inversely proportional to the beam energy squared. Figure 8 shows σ_D for back-up and low- β optics as a function of the distance x_0 between the detector and the beam axis for a beam energy of 51.5 GeV. The sharp fall beyond 70 mm is caused by acceptance limitations due to upstream vacuum chambers.

FIGURE 8
Bhabha monitor cross section σ_D versus monitor distance x_0 from the LEP beam.

3.2 Description and performance of the calorimeters

The operational performance of a compact Si-W sampling e.m. calorimeter has been demonstrated to give a linear energy response to better than 1% and an energy resolution of $(17.6 \pm 0.3)\% \sqrt{\tau/E}$. The parameter τ is the sampling frequency in radiation lengths (r.l.), i.e. the number of r.l. of passive material between two active detectors, while E is the incident electron energy in GeV [1].

For a Bhabha detector which only has to identify particles with the known beam energy, a limited energy resolution can be accepted. Consequently, a limited number of sensitive planes has been chosen and their distribution along the absorbing material is shown in fig. 9.

Five silicon pad detectors (F1–F5) to measure the shower energy are placed between 6 and 14 r.l. of tungsten every 2 r.l. Three silicon-

strip detectors S1, S2 and S3 are placed at 2, 5 and 15 r.l respectively. S1 is used to measure photon fluxes, S2 for the reconstruction of the electron impact positions and S2 or S3 for trigger purposes.

The backside of the calorimeter is protected against SR and off-momentum particles by 30 r.l. of tungsten. A 2 mm lead shielding has later been added around the calorimeters in an attempt to absorb low-energy SR photons that were the cause of sharply increased reverse currents (sect. 3. 4).

A complete calorimeter, as shown in fig. 10, has been tested in a secondary electron beam at the CERN SPS ([7] and [9]). Figure 11 shows the longitudinal shower development for different beam energies and fig. 12 gives the measured intrinsic energy resolution (electronic noise

FIGURE 9 Cross-section of a 15 m horizontal collimator with a calorimeter embedded in its pit.

FIGURE 10
Final calorimeter with associated electronics.

FIGURE 11
Longitudinal deposited energy by electron showers of energy E in the 5 pads of the calorimeter as a function of its depth.

FIGURE 12
Intrinsic energy resolution of the calorimeter as function of the incident electron energy.

subtracted) of the calorimeter, selecting events with fully-contained showers. In this case an intrinsic energy resolution of $64\% \sqrt{1/E}$ has been achieved. For particles impinging on the edge of the calorimeter, which is the case for most of the Bhabha scattered particles, part of the shower energy escapes radially. The measured fraction of the deposited energy from 49 GeV incident electrons versus the impact distance d from the edge of the calorimeter is shown in fig 13.

FIGURE 13
Fraction of the deposited energy in a calorimeter by 49 GeV electrons versus impact d from the calorimeter edge.

3.3 Trigger and data acquisition modes (fig. 14)

The time of every bunch passage is obtained from electrostatic beam pick-ups located at 65 m distance on either side of the IP and is used to open the gate signals for the integrate and hold modules. If the sum signal of the strip detector S2 is larger than the discriminator level, a fast event trigger is formed. The coincidence of the S2 signals from the two calorimeter arms with the signal from the bunch passage is used by the Beam Timing Selection (BTS) module to decide on the type of event seen.

FIGURE 14 Timing and data acquisition logic for the Bhabha monitors.

The BTS allows to select data from a particular bunch pair crossing at the IP and to set the required acquisition frequency of Bhabha and background events, via rate dividers. It also allows to start and stop the time window of the data acquisition period. In addition the BTS contains the logic to measure the accidental pair rate which has to be subtracted from the e^+e^- pair rate to obtain the Bhabha rate in the scaler acquisition mode (see below). This is performed by realizing a coincidence between the signal S2 of one calorimeter delayed by one LEP turn with the signal S2 of the associated calorimeter.

Two acquisition modes are available: the "scaler" and the "ADC" modes.

In the simple scaler mode, the measurement relies on the S2 signals only. By a logical comparison of the input trigger levels the BTS module defines for each bunch crossing the type of event detected: e^+e^- pairs, accidental pairs, single e^+ or e^- or no trigger in either of the two calorimeters. The various event rates are counted with corresponding scalars (VME STR 721). The Bhabha rates are then obtained by subtracting the

number of accidentals from the number of pairs.

In the ADC mode all ADC readings for a batch of ~ 130 events, which are stored in the DRAM's, are transferred to the microprocessors. The relative luminosities are obtained by selecting Bhabha events from the recorded pairs. This is performed by the microprocessors which, after pedestal subtraction and gain calibration (individually for each ADC channel), reconstruct the shower cluster positions, correct the e^+e^- measured energies for the edge effect, select the e^+e^- pairs with energies equivalent to the beam energies and retain colinear events.

3.4 Results

First results from the monitors are given below. The monitors are not yet used during the LEP operation to their full potential.

The deposited energy from a 46 GeV Bhabha-pair event measured in the different silicon detectors of two conjugate calorimeters that form a monitor, is given in fig. 15 showing the detection of an e.m. shower in the ADC mode. The vertical bars represent the longitudinal energy

FIGURE 15

Deposited energy in the two conjugate calorimeters of a monitor by a Bhabha event from a 46 GeV beam.

distribution as seen in the silicon pads and the horizontal bars give the radial shower dimensions measured in the strip planes.

A good trigger efficiency is achieved by adjusting the discrimination thresholds of the S2 hardware sums. The Bhabha rate of a monitor in scaler-mode acquisition is shown in fig. 16 as a function of the discrimination level. Below a certain threshold level the rate sharply increases due to electronic noise. The threshold is set to ~ 20 mV above this level.

The monitors were used to verify the exact crossing of the e^+e^- bunches in all four LEP interacting points by measuring the Bhabha rates versus beam-beam separation in the vertical plane, which was obtained by electrostatic field separators. The result of such a scan in IP2 is shown in fig. 17 for 46 GeV beams at ($\beta_V^* = 7$ cm) low-beta optic. The acquisition time per point was 15 min.

The relative luminosity divided by the product of the two beam currents at the four interaction points is continuously measured by the interaction rate monitors. An example of a long physics run is given in fig. 18. The structure in these signals can clearly be correlated to adjustments of machine parameters which are used to optimize the IP

luminosities. Furthermore, the signals provide very sensitive monitoring of any changes in machine conditions that influence the beam-beam interaction probability.

The results presented in the last two figures are obtained by means of the scaler acquisition mode. The accidental pair rate represent 60 – 80% of the total pair rate.

During LEP commissioning the silicon detectors, in particular the strip planes, suffered from an alarming increase of their diode reverse currents. The behaviour of the strip plane currents after a calorimeter had been placed for a short period near the circulating beam is shown in fig. 19. The fact that these currents recovered when the beams were stopped for several days, suggests a phenomenon of positive charge accumulation induced by low-energy photon background in the detector silicon oxide. This was largely overcome by introducing a few millimetres of lead shielding around the calorimeters (at the expense of Bhabha counting rates) and by biasing the detectors only during data acquisition. The detectors also profited from greatly reduced closed orbit amplitudes around the interacting points thereby reducing the photon backgrounds.

FIGURE 16
Bhabha rates in scaler mode acquisition as function of the discrimination threshold voltage for the S2 hardware sum signals.

FIGURE 17
Bhabha rate versus vertical beam-beam steering in IP 2.

FIGURE 18 Specific luminosity signals from the four LEP interaction points versus time.

FIGURE 19
Initial behaviour of the strip detector diode-reverse currents versus time.

4. Polarimeter

A laser polarimeter has been installed in the LEP straight section, LSS1, in order to measure the degree of transverse beam polarization of the electron beam. The measurement principle [10], as shown in fig. 20, is based on spin-dependent Compton scattering of circularly polarized photons from a laser on the polarized LEP electron beam. For a vertically polarized electron beam up-down asymmetry in the distributions of the high-energy recoil photon occurs depending on the helicity of the laser photons. The measurement of these backscattered photon profiles is performed by silicon detectors.

The layout of the polarimeter is described in [11]. The laser installed in the optical laboratory is operating with a frequency of 30 Hz and the light is guided to the laser interaction region. The backscattered photons reach the detector through a $50 \times 20 \text{ mm}^2$ aluminium window which is 2 mm thick.

4.1 Photon detector

The photon detector shown in fig. 21 is made of movable lead absorbers to convert the high-energy

FIGURE 20
Principle of the laser polarimeter.

backscattered photons into e.m. showers and to attenuate the SR and bremsstrahlung background. Silicon planes are placed behind the absorber in order to detect the deposited energy and to measure the e.m. shower profiles.

The vertical profile used for polarization measurements is obtained with the 2 mm pitch silicon strip plane (S1 H). The horizontal profile used to centre the detector on the photon beam is measured with the 3.1 mm pitch silicon strip plane (S2 V). The distance between the backside of the absorber and the first horizontal strip plane is 0.3 mm and the gap between the two strip planes is 4.4 mm.

The total energy deposition measurement is achieved with five $50 \times 50 \text{ mm}^2$ silicon pads (F1 to F5) positioned behind the strip planes and separated by 2 r.l. of tungsten.

The silicon detectors can be used partly depleted by reducing their bias voltages in order to reduce the collected charge if saturation of the front-end electronics requires this.

The final detector assembly is shown in fig. 22.

FIGURE 21 Cross section of the polarimeter detector.

FIGURE 22
Final polarimeter detector with associated electronics.

4.2 Results

The gate signals for the integrate and hold modules, that integrate the deposited charge in the silicon planes, are opened in synchronism with the electron bunch passage by a signal coming from a beam pick-up station situated at 10 m from the IP. When the laser is triggered, a pulse is sent to the data acquisition system. The data are stored in the local microprocessor and transmitted to a computer in the optical laboratory.

Figure 23 shows the total energy deposited by the SR and bremsstrahlung photons in the horizontal and vertical strip planes as a function of the lead absorber thickness in front of the detector. Usually, a 15 mm lead plate is chosen to reduce the photon backgrounds by two orders of magnitude.

FIGURE 23
Total energy deposited by SR and bremsstrahlung photons in the horizontal and vertical strip planes versus lead absorber thickness.

Backscattered photon profiles in the two strip planes are shown in fig. 24. The asymmetry of the horizontal distribution is probably due to a collimation of the photon beam caused by the exit window. The distribution can be centred by an appropriate correction of the electron beam angle at the laser interaction point. The signal-to-background ratio is about 80 and the number of backscattered photons has been estimated to be ~ 30 per laser shot for a laser intensity of ~ 10 mJ.

The total energy deposited by photons in the two strip planes as a function of the relative laser intensity is indicated in fig. 25, showing a very linear response of the detector energy reading.

FIGURE 24
Photon beam profiles measured by the 2 strip planes.

FIGURE 25
Total energy deposited by the photon beam in the two strip planes versus relative laser intensity.

5. Conclusion

The silicon detectors, their associated electronics and the data acquisition are operating satisfactorily.

The Bhabha monitors are used operationally in the LEP control room for monitoring the relative luminosities in the four interacting points during physics runs and during LEP parameter adjustments. The behaviour of the silicon detector reverse currents is under control. Data analysis is being pursued to make full use of the calorimeter potentialities.

The polarimeter detector has shown its capability of detecting the high-energy backscattered photons and of measuring, with a good resolution and stability, the photon beam distributions.

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