EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-PPE/92-212
11 December 1992

Prototype design, construction and test of a Pb/scintillator sampling calorimeter with wavelength shifter fiber optic readout.

contributed by T. Camporesi, CERN/ PPE Division to
the IEEE Nuclear Science Symposium, Orlando 27-30 October ,1992

A.Benvenuti, V. Giordano, M.Guerzoni, F.L.Navarria(Bologna Univ. and INFN,Italy)
T.Camporesi, P.Vaz (CERN Geneva,Switzerland)
S.J.Alvsvaag, O.A.Maeland, A.Klovning, R.Rongved (Univ. Bergen,Norway)
A.L.Read (Univ. Oslo,Norway)
J.Bjarne, V.Hedberg, G.Jarlskog, I.Kronkvist (Lund Univ.,Sweden)
V.Cassio, D.Gamba, E.Torassa, E.Vallazza, L.Zanini (Torino Univ and INFN,Italy)
L.Lanceri, G.Della Ricca, P.Poropat (Trieste Univ. and INFN,Italy)
M.Bonesini, P.Negri, M.Paganoni(Milano Univ. and INFN,Italy)
A.Gomes, A.Maio, L.Peralta, M.Pimenta, B.Tome(LIP and IST-FCUL Lisboa, Portugal)
S. Bitiukov, S. Gumenyuk, A.Kariukhine, V.Lapin, V.Obraztsov, A.Ostankov,
L.Petrovick, I.Protopopov, V.Semenov, A.Zaitsev (IHEP, Serphukhov,Russia)
D.Colledani, W. Dulinski, R. Turchetta (LEPSI, Strasbourg,France)

Abstract

A prototype for the new DELPHI luminosity monitor has been built and tested. The scope of this prototype was to measure the response of the proposed calorimeter in the region which is most critical for the luminosity measurement, i.e. at the inner edge of the acceptance.

The aim of the new luminosity monitor is to measure the LEP luminosity with per mill systematic uncertainty: this requires experimental biases at the level of 50 μm or less in the definition of the fiducial volume. Even though we plan to use a tungsten mask to define the inner edge of the acceptance, the calorimeter was designed to match intrinsically this kind of accuracy.

A relatively good energy resolution is a must to be able to reject the accidental Bhabha coincidences due to off momentum electrons in LEP.

A cut at 80% of the beam energy should reduce this background to less than 1%.

The technique used ensures good energy resolution and high spatial uniformity. With the prototype we have already achieved better than 2% uniformity in response and an energy resolution of 3% at 45 GeV.

I. INTRODUCTION

The high precision, needed for luminosity measurement at LEP, imposes rather tight constraints on the energy resolution and spatial uniformity of modern Luminosity monitors. The DELPHI collaboration has recently proposed to replace the Small Angle Tagger calorimeter with a detector of novel conception: Small angle Tile Calorimeter (STIC)[1]. This new detector is a sandwich of 3 mm lead converter plates and 2.5 mm thick scintillator tiles. The non uniformity problems of this kind of tower calorimeter have

been solved by two technical choices: the converter plates are continuous, so that the tower structure is determined only by the way the tiles are arranged, and the readout is achieved by means of Wave Length Shifter fibers running perpendicularly to the calorimeter samplings through holes drilled in the scintillator and lead plates. The relatively high non uniformity observed in earlier applications [2] has been avoided by using an optimal density of readout fibers – roughly 1 fiber/cm².

The prototype has been exposed to an electron beam in the CERN West Area with energy varying between 10 and 100 GeV. A Silicon Microstrip telescope[3] was placed upstream of the calorimeter to define the impact point on the front of the calorimeter with a precision better than 50 μ m. This precision is adequate to study the systematics of the calorimeter response with the accuracy required by a 1% luminosity error at LEP.

II.DESIGN AND CONSTRUCTION

The basic unit of the calorimeter is a 'sandwich': the backbone is a vetronite box which provides an external frame and a 0.5 mm supporting wall for the lead converter plates. The 3 mm lead plate is mounted on one side of the wall while on the other side we have in succession: a 120 μ m thick sheet of white Tyvek*), 2.5 mm thick scintillator tiles separated from each other by Al Mylar foils and another 120 μ m thick Tyvek sheet. We have chosen to use spunbonded polyethylene (Tyvek) as a diffusor since it is guaranteed to be completely inert and is not treated with aromatic compounds which could attack the scintillator surface.

The lead plate is coated by an electrolytically deposited (few μ m thick) layer of Nickel and Copper to strengthen its mechanical properties.

Each tile is attached by means of 2 alignment dowels (1 mm diameter, 5 mm long) to the Pb plate. Each tile has been machined from a larger piece of scintillator using a computer controlled tool in the workshops of IHEP Protvino. A sample corresponding to 10% of the finished tiles has been measured using a modified version of a Bubble Chamber scanning table (accuracy 5 μ m) and found to be within ± 50 μ m of the nominal geometry.

The production rate was about 3 tiles/hour per machine.

Each component of the sandwich has throughgoing holes to let the readout fibers pass: the hole diameters, in the various materials, are listed below.

Pb	1.6 mm
Scintillator	1.4 mm
Tyvek	1.6 mm
Vetronite	2.0 mm

The readout fiber were 1 mm diameter Kuraray SCSF Y7 fibers, with F-PMMA cladding, which have an emission peak at ~ 500 nm.

The fibers have a length of 450 mm and were polished using an air cushion diamond mill**) at both ends. One end had an aluminium mirror deposited by sputtering***). The attenuation length of each fiber has been measured individually using a collimated beta source. A typical attenuation pattern is shown in fig 1

Fig 1.: typical attenuation length behaviour

The fibers have been grouped according to their uniformity in the region of interest (15 cm from the polished end to the mirrored end) and the most uniform ones (144 out of 500) were chosen to be inserted in the calorimeter. The total spread in the effective attenuation length is < 15% and the average value is around 2.2 m.

*) Tyvek® is Du Pont's registered trademark for its spunbonded olefin

**) GEBEX, Uster, Switzerland

***). **) PRECISTRAME, Tramelan, Switzerland

Fig. 2: Prototype layout, seen from front face
The dots represent the region where the fibers are inserted in any given azimuthal sector. The bottom part of the figure shows the regions which have been illuminated during the beam exposure

The prototype comprises 50 sandwiches, for a total of 27 radiation lengths, arranged in 3 azimuthal sectors - 22.5° degrees wide - and 4 radial sectors for a total of 12 towers. The inner radius of the calorimeter is 70 mm and the radial distance between each tower, at the front face, is 30 mm. The front face with the tower numbering is shown together with the shape of tiles and the distribution of fibers in fig. 2.

The calorimeter is projective to a point at 2200 mm upstream of the first plate: this implies that the towers form an angle with respect to the horizontal plane which varies between 31.8 and 86.4 mrad. Given that the inclination of the beam with respect to the calorimeter is fixed we chose to have the beam parallel to the edge between the first and second ring of towers in the vertical plane (which will correspond to the inner edge of acceptance for Bhabha events at LEP).

In the horizontal plane the towers and fibers form an angle of 3° with respect to the beam to roughly reproduce the proposed geometry for the final detector in LEP.

For each tower, the fibers are bundled together at the back of the calorimeter by means of a specially developed hexagonal clamp (fig 3). This clamp is fixed on a supporting plate so that the plane formed by the polished fiber ends is parallel to the photocathodes of the readout tubes and at a distance of 7 mm. from it.

Fig. 3: cross section of fiber clamp. The front part of the jaws is made out of PMMA.

We plan to use the natural numerical aperture of the fibers to illuminate the whole active surface of the photocathode: the light comes out from the fiber inside a cone of half aperture of 34.7° . By placing the fiber ends at some distance from the tubes possible non uniformities of the photocathode response are smoothed out.

III.READOUT

Since the detector has to be operate in the DELPHI high magnetic field - 1.2 Tesla- it requires readout devices which can function in such a high field. We have chosen to use tetrode tubes for the final detector and, to simulate the relatively low gain which we expect from such devices (14 at DELPHI field), we have used triodes (Hamamatsu R2148) for the prototype test. The triodes provide somewhat lower gain $-7+10-$ without magnetic field as is the case for the prototype test, but are similar to tetrodes with respect to the signal treatment and the quantum efficiency of the cathode - $< 10\%$ at 500 nm.

We have used the readout chain, preamplifiers, Fastbus shapers and Fastbus ADC cards, developed for the triode readout of the DELPHI Lead Glass Forward Electromagnetic calorimeter (EMF)[4]. The main characteristics of the analog shaping are : peaking time of 1.5 microseconds and baseline restoration times around 10 microseconds.

The data has been read out using the DELPHI standard acquisition system based on the FIP fastbus master [5] and was transferred to the DELPHI online cluster via Ethernet and stored on disk.

The silicon microstrip telescope, used to define the incoming particle trajectory, was readout via a completely different, VME based, acquisition system. The necessary synchronization between the two acquisition systems was achieved by using a common Busy-bar logic. To cross check the synchronization, a 32 bit run and event number broadcast by the VME system was read out by the Fastbus acquisition and recorded in the data collected for each trigger.

Immediately after data taking the two streams of data were processed and the calorimeter information was merged with the tracking information into PAW [6] n-tuples available for further analysis.

IV. DATA SAMPLES AND ANALYSIS

The X5 test beam of the CERN West Area is a tertiary beam which can provide high purity electron beams from 10 to 100 GeV/c. The beam momentum bite is defined by the collimation after the main bending magnet and was set to 2% for these tests. We estimate the dispersion of the beam momentum to be about 0.6%.

The beam intensity was at most 5000 electrons over the 2.4 seconds spill from the SPS. Despite this relatively low rate, the long shaping time of the analog chain caused the superposition of two beam particles in less than 1% of the recorded events. This pileup probability (clearly due to some residual bunching of the extracted beam) might affect the baseline stability. We are planning to study in future tests these effects in greater details. In the present analysis no attempt is made to correct for it. In this respect the results quoted are conservative.

The beam spot RMS was 3.5 mm vertically and 6.0 mm horizontally.

The prototype was mounted on a table controlled by stepping motors and capable of moving in steps of 0.6 μm vertically and 10 μm horizontally.

The Silicon microstrip telescope is formed by 4 pairs of strip detectors (vertical and horizontal strips) covering an area of 3 times 3 cm^2 . Each plane is composed of 25 μm strips readout with a 50 μm pitch.

The distance of the front face of the calorimeter to the last plane of silicon strips was

~ 40 cm. The extrapolation error of a 45 GeV electron track is estimated to be around 40 μm .

The trigger was provided by a simple coincidence of two scintillators (one 3x3 cm^2 and the other 2x2 cm^2) located just in front of the microstrip telescope.

Data was collected to measure the energy resolution and the response uniformity of the calorimeter. In Fig. 2 the layout of the prototype is shown seen from the front face. The dots in the middle sectors indicate the points where the fibers are going through the calorimeter. In the bottom part of the figure the regions which have been illuminated by the beam exposure are hatched. With reference to this figure we have taken data with the beam in the middle of tower 6 and 7 for the energy scan while the rest of the data has been mainly used for studying the spatial uniformity and reconstruction ability of the calorimeter. Data collected at the boundary between 4 towers has been used mainly to correct for the response of the different towers by determining the calibration coefficients which minimize the energy spread.

Noise and calibration

We have also collected calibration data by injecting charge pulses at the preamplifier input and pedestal runs interleaved with test beam runs.

From pedestal runs we could verify that the pedestal width was determined by incoherent noise as the width of the sum over all the channels was the same as the square root of the sum of the squares of the individual pedestal width—shown in fig 4.

From the charge calibration we could establish that the average noise level per channel is ~ 340 electrons which is very close to the best performances observed with these preamplifiers on the test bench.

The noise, summed over all channels, is equivalent to ~ 500 MeV energy deposit. This equivalence depends, of course, on the amount of light collected per GeV of energy converted in the calorimeter and on the gain of the photo-readout. It will become less for the proposed final detector since the gain of the tetrodes is higher than the one of the triodes and we plan to use 3 mm thick scintillator instead of 2.5 mm.

Fig. 4: The distribution of the sum over pedestals: the width is equivalent to an energy spread contribution of ~ 550 MeV

We estimate the photo-electron yield from the photocathode to be 300 electrons / GeV. This estimation is based on the comparison of the charge calibration with an assumed gain of 7 for the triodes. We plan to measure this yield with independent methods in future tests.

Energy scan : resolution and linearity

The energy scan consisted in collecting data at various energies at a tower center. We collected data with beam energies of 10,20,30,45,70 and 100 GeV. The results are reported in Fig 5 where the open dots represent the raw data after calibration, the black dots are after subtraction of the noise contribution and of the beam momentum spread of 0.6% and the crosses are the result of the simulation of our prototype using the GEANT315 package [7].

Both sets were fitted: for the raw data case the value of the noise term estimated from the fit agrees extremely well with the estimation of the expected noise contribution from the pedestal runs as can be seen from the result below:

$$\frac{\sigma}{E} = \sqrt{(0.01 \pm 0.001)^2 + \left(\frac{0.166 \pm 0.006}{E^{1/2}}\right)^2 + \left(\frac{0.050 \pm 0.03}{E}\right)^2}$$

The sampling contribution and the constant term are fitted equally well by the two parametrizations:

$$\frac{\sigma}{E} = \sqrt{(0.010 \pm 0.003)^2 + \left(\frac{0.158 \pm 0.001}{E^{1/2}}\right)^2}$$

$$\frac{\sigma}{E} = (0.0041 \pm 0.0003) + \left(\frac{0.144 \pm 0.002}{E^{1/2}}\right)$$

Fig. 5: Energy resolution. The full lines represent the two fits with and without subtraction of the noise contribution.

The energy linearity is shown in Fig 6a & b. The two parameter fit yields

$$E_{\text{reconstructed}} = (0.9833 \pm 0.0002) E_{\text{beam}} + (0.585 \pm 0.009)$$

The deviation from linearity are shown in fig 6/b. They are below 0.5% for all points except the 10 GeV point. We suspect that some magnet hysteresis might have affected the real momentum of the beam since we did not perform a demagnetization procedure when going from the high energy setting to the low energy one.

Spatial uniformity

Data has been collected with a 45 GeV/c electron momentum in several regions of the detector. The distribution of data collected at the boundary between towers is shown in fig 7 before and after calibration of the gain difference between various channels. The large spread before calibration is mostly due to some channels which had rather low gains in the triode-preamp chain.

Fig. 6: Linearity response: a) Reconstructed energy Vs Beam energy, b) Percentual deviation (we suspect some hysteresis problem with the beam magnets for the point at 10 GeV).

Fig. 7: 45 GeV Energy distribution before and after the channel equalization. The equalization has been obtained by imposing the beam energy constraint when illuminating 4 tower boundaries

The high accuracy of the track definition has allowed a very fine scan over the surface of the detector: we have covered in steps of 0.5 cm. the central line spanning from tower 8 to tower 5. This scan goes over several tower boundaries and directly over many WLS fiber positions

The average energy per tower is shown in fig 8, where one can see the typical shape defined by the energy sharing between adjacent towers when getting close to a border. The average total energy

measured as a function of the vertical position of the beam is shown in fig 9

Fig. 8: Average energy per tower in the central region when scanning along the vertical median line. On the same plot are superimposed the signals from tower 5,6,7 . Note that the binning corresponds to roughly 3 times the resolution on track extrapolation.

Fig. 9: Total Energy versus vertical position of the beam . The scan has been performed over the median line of calorimeter, so crossing several fiber holes. The top arrows indicate the theoretical position of the fiber, while the bottom arrows indicate the boundary locations

The main features of these plots are the following:

- 1) there is very little effect in crossing a border between different towers, thanks to the continuity of the converter (as can be seen clearly at the border between tower 6 and 7).
- 2) going close to a fiber enhances the efficiency of photon collection. This effect dominates over that due to non uniformity in the converter structure where a fiber goes through.

3) The overall non uniformity is contained within a $\pm 2\%$ band. Since the position scan was over the most non uniform region, we expect that the average nonuniformity over the surface of the calorimeter to be less than that.

Fig. 10: Response uniformity when crossing the border between 4 towers. The top plot shows the response as a function of the radius of impact of the electrons and the bottom one as a function of the azimuth. The shaded area shows the region illuminated during this scan with the beam.

The lines represent the $\pm 2\%$ limit.

This is confirmed by the response uniformity across a 4 tower corner shown in fig. 10. There is no evidence of the boundary structure

Space resolution of the calorimeter

A key point to estimate the performance of a Luminosity monitor is the precision with which the calorimeter can reconstruct the impact point of an incoming electron. The dependance of the Bhabha cross section on the lower limit on the

accepted scattering angle is such that, for the region which will be covered by the calorimeter in Delphi, a 1% systematic errors corresponds to 50 μm bias in the reconstructed radial impact. During the present test we have tried to estimate the resolution achievable with the calorimeter structure we propose.^(*)

As an estimator of the radius of impact of the particle we have used the ratio

$$R = \frac{(E_{\text{ring}_{i-1}} - E_{\text{ring}_i})}{(E_{\text{ring}_{i-1}} + E_{\text{ring}_i})}$$

where E_{Ring_i} is the energy deposited in the i -th ring (in the prototype a ring comprises three towers). The behaviour of this variable versus the impact point predicted (r) by the microstrip telescope is shown in fig. 11.

Fig. 11: The variable R described in the text vs the radial impact as reconstructed from the microstrip telescope.

As can be seen from the figure this estimator is more precise around the edge between two rings, as intuitively one would expect. Since the transverse shape of electromagnetic showers is best represented by exponentials, we have used the hyperbolic function

$$R = a \cdot \sinh(b \cdot r + c) + d$$

to fit the $R(r)$ behaviour. The inverse of this function can be used to estimate the impact point $r'(R)$ using the calorimeter information. The plot of the difference $\Delta = (r' - r)$ is shown in fig. 12 for the

^(*) As specified in [1] we are planning to use a Tungsten mask to define the inner edge of the acceptance. The calorimetric measurement would be a redundant cross check.

electron tracks entering in an interval of ± 1 mm around the border.

Fig 12: resolution of calorimeter reconstructed position when the incoming 45 GeV electron is within ± 1 mm from edge between ring 1 and ring 2.

The resolution observed ($\text{RMS} < 200 \mu\text{m}$) indicates that the calorimeter has really the potential to achieve better than $50 \mu\text{m}$ bias in the impact point reconstruction: the space resolution has to be understood – and reproduced by the simulation – to better than 25%

Fig 13: The reconstruction resolution as a function of distance from the edge between two rings for 45 GeV electrons

The resolution is worsening rapidly when moving away from the border as presented in fig. 13, still remaining better than ~ 1 mm. The dependence of the resolution in the interval of ± 1 mm around the border versus the electron energy is presented in fig.14.

Fig 14: The resolution for particles entering in an interval of ± 1 mm from the edge between ring 1 and ring 2 versus energy of the incoming electron.

One can see that at energies typical of the future LEP200 accelerator the calorimeter alone will allow the determination of the luminosity at much better than the desired 1% level (which correspond to controlling the systematic to better than $500 \mu\text{m}$).

In this particular test we were not equipped to survey the absolute position of the calorimeter with respect to the microstrip telescope to be able to assess fully the systematic accuracy of the position reconstruction using the calorimeter. We are planning to implement an absolute reference system for a future test.

V. CONCLUSIONS

We have built and successfully tested a prototype of the proposed luminosity monitor for the DELPHI detector at LEP. The energy resolution measured ($\sim 3\%$ at 45 GeV) is perfectly adequate for rejecting the off momentum beam background while maintaining full efficiency for the Bhabha events.

The spatial uniformity response - better than $\pm 2\%$ in the worst case - is adequate for the systematic accuracy needed at LEP.

ACKNOWLEDGEMENTS

The contruction of the calorimeter mechanics was done in the IHEP (Protvino) workshops and it was only thanks to the their effort that we could get the prototype ready in time.

We would like to thank the technical staff of the INFN section of Bologna for the excellent work produced and in particular S.Finelli, O.Cinelli, A.Pieretti, S.Serra,G.Pancaldi and O.Baglioni.

We acknowledge the support of prof. M.Schaeffer for the beam tests and the technical support -and many usefull discussions- from R. De Salvo.

We also acknowledge the assistance of A.Enriques during the test of the fibers.

Last but not least we would like to thank the technical support of the DELPHI online team and in particular C. Gaspar, I. Lippi and W. Bell for their help in setting up the acquisition system.

REFERENCES

[1]The DELPHI Collaboration,"Proposal for the replacement of the Small Angle Calorimeter of DELPHI", CERN/LEPC/92-6, LEPC/P2-Add.1, 8 May, 1992

For a general description of DELPHI:

P.Aarnio et al., "The DELPHI detetctor at LEP", Nucl.Inst. and Meth. A303(1991)

[2]B.Loher,S.Weissenrieder,F.Barreiro and E.Ros,"An elcctromagnetic calorimeter with wavelength shifting fiber readout", Nucl. Instr. and Meth. A254 (1987) 26

[3]For a description of the performance of the Silicon microstrip telescope see for example:

M. Colledani et al., " A high resolution Silicon Telescope", LEPSI Note, CRN Starsbourg - to be published.

R.Brenner et al., " Measurement of spatial resolution of double sided AC-coupled silicon microstrips detectors", presented at the 6th European Symposium on Semiconductor Detetctors, Milan, February 24-26 1992 to be published in Nucl. Instr. and Meth A.

[4]G. Barichetto at al., "A low noise amplification chain for the vacuum phototriode readout of the DELPHI Lead-Glass calorimeter", Nucl. Instr and Meth. A254 (1987)

I.Lippi et al. "The Multiplexed ADC system and the Fastbus readout for the DELPHI Froward Electromagnetic Calorimeter", Nucl.Inst. adn Meth. A286 (1990)243

[5] Ph. Charpentier et al., "The DELPHI Fastbus data Aquisition system", Proceedings CHEP 91, Tsukuba, pg. 643-652

M.Jonker et al., " Architecture and performance of the DELPHI data Acquisition and control system", Proceedings CHEP91, Tsukuba, pg.619-626.

[6]"PAW" CERN Program library Long writeup, Q121. Can be requested from CERN program Library Office, CN division, CH1211, Geneva 23

[7]R. Brun et al., "GEANT3", DD/EE/81-1, CERN 1987. Can be requested from CERN program Library Office, CN division, CH1211, Geneva 23