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for the photon spectrometer LEDA
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We report on the design, construction, and test of a new gain monitoring system developed for the 10 000-module lead glass calorimeter in the WA98 experiment. The system combines precision monitoring and modularity according to the general detector design. It is based on pulsed LEDs and photodiodes. The complete system was successfully used in an electron calibration and during the first Pb-ion beam time at the CERN SPS.

1 Introduction

The WA98 collaboration at the CERN SPS studies Pb-Pb interactions at 160 A GeV[1]. The major goal of the experiment is the measurement of direct photons in these reactions, which yields information about the hot and dense interaction zone. Such a measurement in the high-multiplicity environment of nuclear reactions requires high-precision photon detection.

It has been shown in the WA80 experiment that the measurement of direct photons in heavy-ion reactions with a lead glass calorimeter is feasible [2,3]. The first lead glass detector used for this purpose (SAPHIR) is extensively described in Ref. [4]. We also learned in this experiment that the gain stability and gain control are crucial for obtaining the needed precision. While the first issue was addressed by developing a new high-voltage power supply [5], the second is the subject of this paper.

The monitoring system for the WA98 photon spectrometer has to match the following criteria:

- (i) It has to provide gain control for the 10 000 phototubes with better than 1% accuracy.

- (ii) It should allow a timing calibration of better than 300 ps.
- (iii) It should be of the same modular structure as the mechanical design of the spectrometer (*supermodules* of 24 blocks) to allow independent transportation of these units while keeping the calibration.
- (iv) It has to be reliable and should need minimal maintenance effort.
- (v) It should foresee a possibility of linearity checks.

To meet these requirements the monitoring system is based on pulsed LEDs. LEDs have the big advantage over a nitrogen laser (as used e.g. in the SAPHIR detector in WA80) that the intrinsic pulse-to-pulse fluctuations are negligible. In addition the LED light is monitored by photodiodes incorporated in the supermodules.

2 Design

2.1 The photon detector

The WA98 photon spectrometer LEDA¹ consists of 10 080 individual TF1 lead glass blocks equipped with FEU-84 photomultipliers (both the lead glass and the phototubes are provided by the Kurchatov Institute, Moscow). It is intended to use the same detector material both in the fixed-target experiment at CERN and later in the PHENIX experiment at the RHIC collider. The very different geometrical requirements of the two experiments make a flexible detector structure mandatory. It was therefore decided to assemble the lead glass in subunits of 6×4 modules, which serve as independent detectors, but that could be mounted as a large structure without additional inactive material.

A phototube housing and a thin front plate were glued to the lead glass blocks of $4 \times 4 \text{ cm}^2$ cross section and 40 cm length. The blocks were then wrapped with aluminized Mylar and shrink tube, and 24 modules were glued together with carbon fibre and epoxy resin to form a self-supporting unit, called a *supermodule* (see Fig. 1). Surrounding steel plates to house the phototubes and bases were incorporated during the gluing process. The front plate of each lead glass module contains a hole which serves as an entry for the light to be used for gain monitoring.

A laser-based monitoring system is not adequate for the modular structure of the detector, as it would require the transfer of the laser light through light fibres and removable connectors to the detector supermodules. Such connec-

¹ LEadglass Detector Array.

Fig. 1. Exploded view of a lead glass detector supermodule (description see text).

tors, however, do not yield a coupling with a sufficient reproducibility of the intensity. Therefore it was decided to use LEDs as light sources that would be monitored by photodiodes. Each supermodule is equipped with an individual front-end part of the monitoring system including three LEDs and a PIN photodiode with preamplifier. The light of all three LEDs is distributed to 24 phototubes and the photodiode simultaneously. Fig. 2 shows the design of the front-end part of the monitoring system.

2.2 LEDs

For monitoring purposes it is desirable to have light pulses as similar as possible to the Čerenkov signals. Unfortunately, this is not possible with a single LED. In order to reproduce the fast pulse shape, we have therefore decided to use a yellow LED of very high light output and fast response and to drive it with a very fast pulse generator (avalanche pulser - see below).

The yellow light from the LED does not match the spectrum of the Čerenkov

Fig. 2. Design of the front-end part of the monitoring system mounted on a super-module of the lead glass detector.

light. However, this is not considered important for correcting short-term gain variations, as they are not expected to depend on the spectrum of the detected light. To check also for possible changes in the spectral sensitivity of the photocathodes due to ageing effects, we have included a blue LED in our design. Available blue LEDs, however, have both low light output and slow response and are incapable of delivering a fast pulse of sufficiently high intensity, so this LED has to be used in a different operation mode with comparably long pulses.

In addition, the avalanche pulser cannot be varied in intensity, so another yellow LED is used with a different pulse generator to allow for linearity checks. Details of the two types of LEDs used are given in Table 1.

The dominant effect that causes changes in the light pulses is the temperature

dependence. LEDs are known to have an exponential dependence of their output intensity on the temperature:

$$I(T) = I(25^{\circ}\text{C}) \cdot \exp[k(T - 25^{\circ}\text{C})].$$

The temperature coefficients k for the LEDs used can be found in Table 1. The effective band gap is also inversely correlated to the temperature, so that the emission spectrum of the LED is shifted to longer wavelength with increasing temperature. However, typical shifts are approx. $0.1 \text{ nm}/^{\circ}\text{C}$ [6], which is sufficiently small to be ignored for our purpose.

Table 1
Technical data of the LEDs

Type	HP HLMA-DL00	HP HLMP-DB15
Material	AlInGaP	SiC
Peak wavelength	592 nm	468 nm
Halfwidth	15 nm	$\approx 60 \text{ nm}$
Response time	13 ns	500 ns
DC current	30 mA	50 mA
Transient current (10 μs)	100 mA	500 mA
Luminous intensity (20 mA)	650 mcd	12 mcd
Radiant flux (20 mA)	0.4 mW	0.016 mW
Rel. no. of photoelectrons	1	0.06
Temperature coeff.	$-0.01/^{\circ}\text{C}$	$-0.011/^{\circ}\text{C}$

2.3 Pulse Generators

The effective response time of the blue LED has been studied with an electronic pulser (avalanche pulser) with a rise time of a few nanoseconds. LED pulse rise times of the order of 25–30 ns have been achieved. However, the total pulse width is still larger than 400 ns and the intensity of the LED is very low, which makes this mode of operation unusable. For the yellow LED, rise times of 8–10 ns and total pulse widths of 30–40 ns have been reached at a very reasonable intensity with a similar avalanche pulser.

The behaviour of such an avalanche pulser, however, is fully determined by the properties of the electronic components, namely the final stage transistor

and the LED. There is no intensity variation possible — either the supplied voltage is below a limit, and fast pulses are not achieved, or the voltage is high enough that the avalanche effect sets in. With a further increase of the voltage there is only very little variation in the output until the transistor or the LED are destroyed. Therefore such a pulser has no possibility of varying the intensity for linearity checks.

Variable pulsers naturally provide slower signals. For the yellow LED a pulser has been built, which yields pulses of ≈ 200 ns width, while the intensity can be varied via the power supply voltage of the final stage transistor. For the blue LED, however, only pulses of $\approx 1 \mu\text{s}$ width yield sufficient intensity to be distributed to 24 phototubes.

Because of the above-mentioned facts three different pulse generators are implemented:

- (i) An avalanche pulser (AP) for use with a yellow LED,
- (ii) a slow pulser (SP) with variable intensity for use with a blue LED, and
- (iii) a fast pulser (FP) with variable intensity for use with a yellow LED.

2.3.1 Avalanche pulser

The avalanche pulser (AP) has similar pulse shape characteristics to Čerenkov pulses (see Fig. 3) and should allow timing calibration. It is based on a design originating from INFN/Pisa and modified at the KFA Jülich [7] and was adapted to the needs of our experiment. The voltage supplied to the final avalanche stage is 126 V.

The pulsers are built as multiple (16-channel) NIM units requiring an external trigger signal. The layout takes care of the timing requirements, i.e. it is designed symmetrically for all channels avoiding different path lengths for different channels.

Pulses from the FEU-84 phototubes show a rise time of $\tau_R \approx 10$ ns and a fall time of $\tau_F \approx 25$ ns. The timing resolution of these pulses has been measured using constant fraction discriminators to be $\sigma_t \leq 200$ ps, which is probably dominated by transit time variations in the phototubes.

2.3.2 Slow and fast pulsers

The slow pulser (SP) is used with the blue LEDs to provide light pulses of wavelengths similar to that observed from Čerenkov light in lead glass. A monovibrator defines the pulse width and feeds an amplifier with a high power

Fig. 3. Pulses observed at the phototube anode (a) for the avalanche LED pulser and (b) for Čerenkov light emitted by an electron shower of 10 GeV energy.

FET as the final stage transistor, which can be used up to voltages of 60 V. The total pulse width is $\tau_T \approx 1 \mu s$.

As the width of the ADC gates for the phototube signals are in the range of 250 ns, they will not collect the full charge. The gate for the blue LEDs is thus positioned on the plateau of the pulses, so that one obtains a “quasi-DC” mode of operation. The influence of jitter in the relative timing is thus negligible.

One NIM unit houses 16 channels. It is supplied with external power and an external trigger.

The fast pulser (FP) provides additional redundancy and the possibility of linearity checks. It uses a design similar to the SP with the difference that the

monovibrator feeds directly the final transistor stage. No amplifier is needed because the yellow LED yields much higher light intensity at relatively small currents. The total pulse width is set to $\tau_T \approx 200$ ns with rise and fall times smaller than 50 ns. The pulse height can be varied by supplying different voltages ($U = 5\text{--}35$ V) to the final stage.

For both pulse generators external power supplies are used that allow the setting of the output voltage both manually and by computer via a parallel interface. This provides the option of on-line variation of the intensity of the LEDs. The slow and fast pulser systems were developed at the IKP Münster.

2.4 Distribution system

The light distribution to the phototubes is achieved by very simple means. The LEDs are mounted inside a plastic cover sitting at the front side of the supermodules (see Fig. 1 and 2). They shine onto the inner surface of this cover which is coated with a highly reflective, diffusing paint. The front side itself is covered by a mirror foil to keep light absorption minimal. The light enters the lead glass modules through holes in the mirror foil and the plastic front face. Intensity variations at the different hole locations in the supermodule are compensated by properly dimensioned hole sizes.

The three LEDs are mounted in thin metal tubes for shielding to avoid RF crosstalk. Each LED is connected via a single RG174 cable with the pulse generators.

2.5 Reference detector

Although the short-term variations of the LED intensities are very small, the long-term variations (temperature drifts, ageing) require a reference detector that monitors the LED intensity.

This is done by a photodiode which is mounted inside the plastic cover. In order to better match the different light intensities of the three pulse modes, a yellow filter is mounted in front of the photodiode. In this way, the light from the slow pulses of the blue LED, which would yield much larger integrated intensity than the other two pulse modes, is attenuated to about the same effective charge signal as observed from the fast LED pulses.

A PIN photodiode (S1223-01 from Hamamatsu) is used as the light detector. Technical data of this component are given in Table 2. Each photodiode is controlled by a temperature sensor read out via a driver into scanning ADCs.

Table 2
Technical data of the PIN photodiode

Type	Hamamatsu S1223-01
Area	$3.6 \times 3.6 \text{ mm}^2$
Dark current ($U_R = 20 \text{ V}$)	20 nA
Terminal capacitance ($U_R = 20 \text{ V}$)	20 pF
Package	TO-5
Peak wavelength	960 nm
Spectral range	320–1100 nm

2.5.1 Readout

The photodiode is mounted on a printed circuit board together with a hybrid preamplifier and a twisted-pair driver. The preamplifier is shielded by a metal box. The whole PCB is located in a plastic housing at the outer front of the supermodule. The twisted-pair driver provides a groundless signal and can feed a cable of up to 50 m length to the shaper. The preamplifier is equipped with a test input, which allows one to monitor the stability of the readout electronics. Electronic tail pulses are distributed to all preamplifiers to monitor the readout chain, and to reference spectroscopy amplifiers. The shapers are housed in groups of 24 channels in a single NIM unit and are directly connected to peak-sensing ADCs. Currently, a LeCroy 2280 ADC system is used.

The hybrid components are supplied by Vitrohm (Pinneberg, Germany) and have been developed by MPI Munich for the readout of CsI crystals in the Crystal Barrel detector. Details of the readout components are given in Table 3.

3 Performance and test results

The full detector system consists of 420 Supermodules, each equipped with three LEDs driven by independent pulse generators and one photodiode with preamplifier and temperature sensor. The system was implemented and operated successfully in calibration beam times in 1993/94 and in the first Pb-beam time in late 1994.

Table 3
Technical data of the diode readout components

Preamplifier	Vitrohm 559-064
Gain	0.8 V/pC
Noise (20 pF, shaping 1 μ s)	200 e ⁻ RMS
Small signal rise time	10 ns
Output impedance	< 50 Ω
Twisted pair driver	Vitrohm 559-068
Small signal rise time	20 ns
Input impedance	2 k Ω
Output impedance	50 Ω
Shaper	Vitrohm 559-067
Gain	27
Input impedance	2 k Ω
Output impedance	< 20 Ω
Output FWHM	5 μ s

3.1 LED pulse fluctuations

The fast avalanche pulses from a yellow LED observed by a phototube show a Gaussian pulse height distribution. The standard deviation of these distributions is generally below 2% (Fig. 4a). The mean value of the amplitude corresponds to ca. 2000–3000 photoelectrons, so that the dominant part of the fluctuations is attributed to purely statistical effects.

The pulse-to-pulse variations of the other pulse types are slightly larger at comparable mean values — time jitter of the pulses relative to the ADC gates is most likely responsible for this. However, the fluctuations are still small enough (2-3%) to provide good monitoring capabilities.

3.2 Photodiode performance

The very small fluctuations of the LED intensity can also be verified from the photodiode pulse height spectra (Fig. 4b) — here standard deviations are

Fig. 4. Distribution of relative standard deviations of the avalanche pulse height spectra (a) for all phototubes and (b) for all PIN-photodiodes.

less than 1% for all channels. Typical pulse heights of fully amplified signals are a few volts, while the noise level here is about 30 mV peak-to-peak. The major internal source of noise in the photodiode readout is the feedthrough of the ripple of switching power supplies used for the fanouts feeding the electronic test pulses to the input of the preamplifiers. This noise is, however, not problematic for our system.

The pulse height variations of the LEDs induced by temperature changes are not critical, because the light output is controlled by the photodiode. Possible changes in the quantum efficiency of the photodiode itself, however, are not a priori excluded and would have an influence on the gain determination. Although the manufacturer of the photodiode claims that the diode shows no temperature dependence, we have investigated this further.

Fig. 5. Ratio of pulse heights measured in two different PIN photo diodes as a function of the temperature difference. A very weak decrease of the intensity with increasing temperature is visible. Also shown is a straight line fit.

In a test setup two photodiodes with preamplifiers and temperature sensors — the same design as used in the monitoring system — were mounted in two boxes which could be independently regulated in temperature. Both photodiode simultaneously measured light pulses from one LED. The two photodiodes were then exposed to different temperatures in the range of 10–60°C for several hours and the relative pulse heights A_1 and A_2 were measured.

Fig. 5 shows the pulse height ratio $A_{\text{rel}} = A_1/A_2$ as a function of the temperature difference ΔT extracted from these measurements. A straight line fit to these data shows a decrease of the amplitude measured in one photodiode by 0.0077%/°C. For realistic temperature variations in the experiment, which should not exceed 10° C, the effects on the photodiode are therefore negligible.

Fig. 6. Reconstructed energies for different relative gain settings and for different beam times (see text).

3.3 System stability and energy resolution

Parts of the whole detector have been calibrated at two different times separated by half a year. These measurements allow one to check the reliability of the calibration performed with the described monitoring system. In addition, the gain of the phototubes used has been changed by changing the high voltage, so that the ability of the monitoring system to correct for gain drifts can be investigated. Fig. 6 shows the deviation of the reconstructed electron energies

$$\frac{\Delta E}{E_0} = \frac{E_{\text{reconstr}} - E_0}{E_0}$$

for different gain settings, where E_0 corresponds to the electron energy defined by the first measurement, i.e. 10 GeV. The calibration information from the first measurement was used to correct for the others. It can be seen that even for rather large gain variations the correction can be done to better than 0.5%.

The energy resolution of the full detector measured in this electron calibration is shown in table 4. It can be described by

$$\frac{\sigma(E)}{E} = \frac{(5.5 \pm 0.6)\%}{\sqrt{E/\text{GeV}}} + (0.8 \pm 0.2)\%.$$

Table 4

Energy resolution measured in a calibration beam time with electron beams of different energy.

Energy (GeV)	3	5	10	20
$\sigma(E)/E$	4.01 ± 0.40	3.27 ± 0.10	2.63 ± 0.08	2.00 ± 0.13

4 Summary

A high-precision gain monitoring system has been designed and constructed for the 10 000 module lead glass calorimeter LEDA in WA98. The system fits the modular structure of the whole detector. It provides gain monitoring to better than 1% accuracy. It yields information on the linearity of the phototubes and their readout. The response on light of different wavelengths can be investigated.

The system meets all the requirements of the detector monitoring for a large number of phototubes. Its performance in calibration beam times and the first lead-ion run has been shown to be very good. The small intrinsic fluctuations allow one to recognize gain variations on a very short time scale — i.e. from a few pulses. The reliability of the whole system on longer time scales (> months) appears to be good and should allow the transfer of the detector calibration to the PHENIX experiment later on.

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