V.A. Batarin, J. Butler[1], A.M. Davidenko, A.A. Derevschikov, Y.M. Goncharenko,
V.N. Grishin, V.A. Kachanov,V.Y. Khodyrev, A.S. Konstantinov, V.A. Kormilitsin,
Y. Kubota[2], V.S. Lukanin, Y.A. Matulenko, Y.M. Melnick, A.P. Meschanin,
N.E. Mikhalin, N.G. Minaev, V.V. Mochalov, D.A. Morozov, L.V. Nogach,
A.V. Ryazantsev [4], P.A. Semenov, V.K. Semenov, K.E. Shestermanov, L.F. Soloviev,
S. Stone[3], A.V. Uzunian, A.N. Vasiliev, A.E. Yakutin, J. Yarba[1]

(BTeV Electromagnetic Calorimeter Group)

DESIGN AND PERFORMANCE OF LED CALIBRATION SYSTEM PROTOTYPE FOR THE LEAD TUNGSTATE CRYSTAL CALORIMETER

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[1] Fermilab, Batavia, IL 60510, U.S.A.
[2] University of Minnesota, Minneapolis, MN 55455, U.S.A.
[3] Syracuse University, Syracuse, NY 13244-1130, U.S.A.
[4] Corresponding author, email: ryazants@ihep.ru

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Abstract

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A highly stable monitoring system based on blue and red light emitting diodes coupled to a distribution network comprised of optical fibers has been developed for an electromagnetic calorimeter that uses lead tungstate crystals readout with photomultiplier tubes. We report of the system prototype design and on the results of laboratory tests. Stability better than 0.1% (r.m.s.) has been achieved during one week of prototype operation.

Keyword: Light emitting diode; Monitoring system; Lead tungstate; Calorimeter; Energy calibration

Аннотация

Батарин В.А., Батлер Д., Давиденко А.М. и др. Конструкция и характеристики прототипа калибровочной системы на светодиодах для калориметра на кристаллах вольфрамата свинца: Препринт ИФВЭ 2005–33. – Протвино, 2005. – 10 с., 6 рис., 1 табл., библиогр.: 16.

Разработана высокостабильная мониторная система с использованием синего и красного светодиодов и оптических волокон-световодов для электромагнитного калориметра на кристаллах вольфрамата свинца с фотоэлектронными умножителями для съёма информации. Представлены устройство прототипа и результаты его лабораторных испытаний. Стабильность системы лучше 0.1% (r.m.s.) была достигнута за неделю непрерывной работы.

1. Introduction

Lead tungstate (PbWO$_4$, PWO) scintillating crystals are known as an appropriate material for use in a total absorption shower detectors. Electromagnetic calorimeters (EMCAL) made of these crystals have superb energy and spatial resolutions due to the unique combination of the PbWO$_4$ physical properties [1]. Several high energy physics experiments, such as ALICE and CMS at the CERN LHC or PANDA at GSI, have decided to build their calorimeters with the use of PWO [2, 3, 4]. The BTeV project at the FNAL Tevatron Collider, recently terminated by the U. S. Dept. of Energy, intended to use these crystals [5].

Unfortunately, lead tungstate crystals although relatively radiation tolerant, do lower their light output when exposed to radiation and recover when the radiation source is removed. Extensive studies performed at the Institute for High Energy Physics (IHEP) in Protvino, Russia, confirmed that the PWO light output changes with the irradiation dose rate. Dedicated measurements showed that degradation of light output in PWO crystals under pion irradiation with dose rates up to 20 rad/h occurs due to light transmission loss only, rather than changes in the scintillation mechanism [6]. Further complications arise because at the same irradiation intensity, changes in light output may vary from one crystal to another [7, 8, 9]. In order to maintain the intrinsic energy resolution, therefore, the system must be continuously calibrated. In this paper, we discuss the preferred solution for BTeV. This technique can be applied for any detector with similar operational conditions.

The BTeV calorimeter was designed to cover the space with a radius 1.6 m near the beam axis, about 220 mr of angle from the interaction point. There were approximately 10,000 PWO crystals coupled with photomultiplier tubes (PMT). About 90% of crystals would suffer from radiation with dose rates less than 20 rad/h. The expected energy resolution of the EMCAL was $1.7\%/\sqrt{E} \oplus 0.55\%$, and the accuracy of the energy calibration should be better than 0.2%.

Monte-Carlo studies show that electrons and positrons produced in physics events, mainly from semileptonic B-decays or from photon conversions near the interaction region, can be successfully used to calibrate the detector in-situ [10]. The amount of time required to collect sufficient samples would be significantly vary in different areas of the EMCAL but even in the

worst case scenario would not exceed one day period. However, the calorimeter would need to be continuously monitored within these time intervals or during Tevatron shutdown periods.

In addition to the crystals light output change, PMT gain instabilities could deteriorate the performance. A usual way to track the PMT gain variations is the use of a monitoring system with a light pulser. If a light pulse could be sent to the PMTs directly, it would be relatively easy to measure PMT gain changes. However, in our case the crystals more than cover the entire detection surface of the mating PMTs; thus the only solution would be to send light to the PMT photocathodes through the crystals. Therefore the same monitoring system that is used to measure the radiation effects needs to be used to monitor the PMTs.

To monitor crystal light output changes, we use a blue light pulser with a wavelength close to the 430 nm emission peak of the $PbWO_4$ crystal. Since these light pulses are detected by PMTs, what we measure is the change in the product of the PMT gain and the crystal transparency. To monitor the PMT gain changes we use a red light pulser, since the red light transmission in the crystals changes much less due to radiation than the blue light transmission [11]. In our test beam studies, the separation of these two sources of signal variations was crucial and allowed us to study the changes in the crystal properties alone. Our experience with a blue-red light pulser system at the test beam facility is discussed in [7].

Taking into account the conditions described above we can summarize the main requirements for the monitoring system light pulser:
- high luminous flux for red and blue (close to 430 nm) light pulses to be able illuminate at least 2600 fibers of the light distribution network providing PMT signals equal to those from 20 GeV electrons;
- non-uniformity of the light spot illuminating the bunch of fibers should be not more than 10%;
- stability at the level of $2 \cdot 10^{-3}$ over a day.

We decided to design a monitoring system with the use of light emitting diodes since LED pulsers provide a very reliable operation and required stability as it was shown in [12]. The whole system should consist of four identical LED pulser modules, each monitoring a quarter of calorimeter. Only one module would be powered in a given time interval. This solution allowed to stay within the bandwidth of the data acquisition system (DAQ) while collecting monitoring data. The prototype of such module was designed and tested at the Institute for High Energy Physics in Protvino.

2. Prototype Design

The light pulser prototype is shown schematically in Fig. 1. The system includes:

- blue and red LEDs;
- two LED drivers;
- light reflector;
- mixing light guide;
- two reference silicon photodiodes;
- bunch of optical fibers;
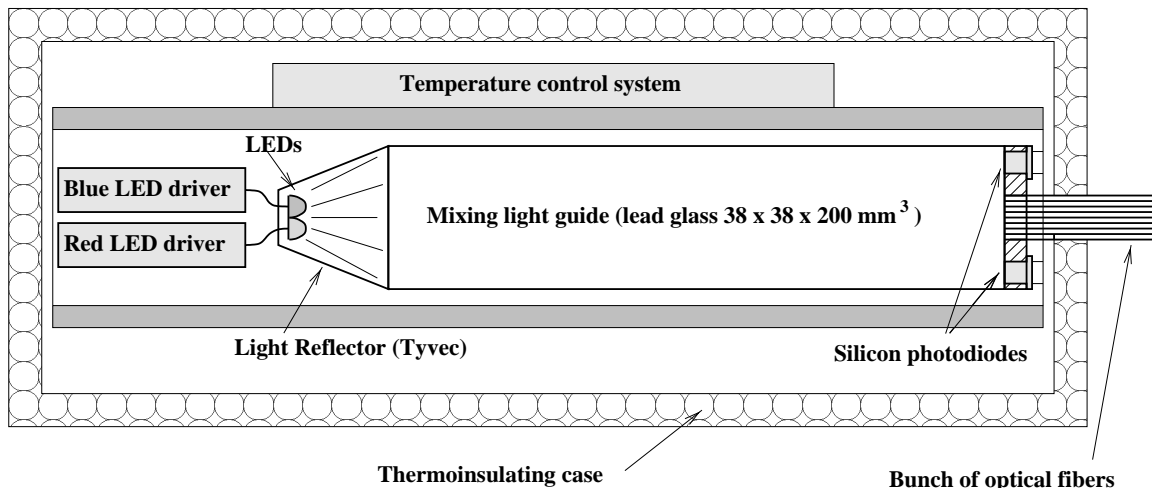- temperature control system;
- thermoinsulating case.

Figure 1. Block diagram of the LED pulser.

Powerful blue and red LEDs from Lumileds Lighting, USA, illuminate optical fibers and reference photodiodes through a bar of lead glass with the dimensions of $38 \times 38 \times 200$ mm^2 which was used as a light mixer. To improve light collection in the mixer, LEDs were placed inside a square pyramid with a reflecting internal surface near the apex. The cross-section of the light mixer allows to illuminate simultaneously about 3000 optical fibers of 0.4 mm diameter. We decided to use silica fibers FIL300330370 by Polymicro Technologies, USA [13]. They have a core of 300 micron diameter and an aluminium buffer providing excellent mechanical strength. According to the results of the radiation hardness measurements with a γ-source obtained by the CMS ECAL group, these fibers keep their light transmittance at the constant level up to 12 Mrad of absorbed dose [14]. This is very important because some part of fibers would be irradiated with high dose rates during the setup operation.

Technical parameters of the LEDs are given in Table 1 [15]. Besides the exceptional luminous fluxes, we found that two additional features of the Luxeon technology are very important for our purposes: very long operating life (up to 100,000 hours in DC mode) and small temperature dependence of the light output (less than 0.5%/°C).

The electronic circuit for the LED driver is shown in Fig. 2. The drivers of red and blue LEDs are identical. They are triggered by pulses of standard NIM-logic levels. Each driver includes a shaping amplifier determining the duration of the light flashes and an output powerful transistor (MOS FET). The transistor switches LED to a voltage source adjustable in a range up to +50 V which allowed us to tune the necessary brightness of the light pulses.

An essential element of the light monitoring system is a stable reference photodetector with a good sensitivity at short wavelengths which measures light pulses amplitude variation in time. Silicon PN-photodiodes S1226-5BQ by Hamamatsu, Japan, are well suited to this task because they have high ultraviolet and suppressed infrared sensitivity, low dark current and small temperature coefficient (less then 0.1%/°C) in the range of wavelengths from 200 to 700 nm [16]. The rather large (about 6 mm^2) sensitive area of this photodiode allows us to work without preamplifiers, thus, improve a stability of the reference system itself. In the prototype, we used two photodiodes attached to the output window of the light mixer in the corners.

Table 1. The properties of LEDs used in the light pulser [15].

LED Property	LXHL-PR02 (Royal Blue Radiometric)	LXHL-PD01 (Red)
Brand	Luxeon V Emitter	Luxeon Emitter
Typical Luminous Flux		44 lm (@350 mA)
Typical Radiometric Power	700 mW (@700 mA)	
Radiation Pattern	Lambertian	Lambertian
Viewing Angle	150 degrees	140 degrees
Size of Light Emission Surface	5×5 mm^2	1.5×1.5 mm^2
Peak Wavelength	455 nm	627 nm
Spectral Half-width	20 nm	20 nm
Maximum DC Forward Current	700 mA	350 mA

Our previous studies showed that temperature variations deteriorate the performance stability of the LED monitoring system [12]. Therefore we designed a heat insulated case with a possibility to control temperature inside it. A simple electronic circuit with a thermistor in the feedback has been placed in the same case. The operating temperature inside the case should be higher than expected maximum of the room temperature since the system contains only heaters. We expected that temperature variation in the BTeV experimental hall would be relatively small (few degrees) over the data taking period, so the suggested solution is adequate.

Figure 2. LED driver circuit.

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3. Test setup

Our test setup consisted of the LED pulser prototype and a lead tungstate crystal coupled with a PMT Hamamatsu R5800, all placed in a light-tight box. Instead of a fiber bunch, we used one silica optical fiber to transport light from the output window of the light mixer to the crystal edge. The crystal and the PMT were taken from the 5×5 calorimeter prototype tested with a beam earlier. Thus, we knew approximate correspondence between an energy of electrons hitting the crystal and amplitude of the anode signal for the fixed PMT gain. The DC voltage source was common for two LED pulsers. Its output level was set to the value which gave the PMT anode signal from the blue LED equivalent to that from a 20 GeV electron.

Our data acquisition system was described in detail in [1]. We used LeCroy 2285 15-bit integrating ADC to measure signal charges from the PMT and photodiodes over 150 ns gate. Besides, temperature was measured continuously during data taking with the use of five thermosensors placed in different locations. One of them provided an information about room temperature, another one was installed near the photocathode window of the PMT. Three other sensors performed temperature measurements inside the prototype case, namely: near the LEDs, near the photodiodes and at the surface of the heater.

4. Experimental results

4.1. Light spot uniformity

Uniformity of the light distribution over the output window of the light mixer was measured by means of manual surface scan accomplished with a single optical fiber with the step size of 2 mm. The scan area was 34×34 mm^2. Light signal was detected by the PMT and the pulse heights were measured with a scope. The shape of the blue LED signal at the anode of the PMT is shown in Fig. 3. The distribution of measured pulse heights is shown in Fig. 4. The r.m.s. of this distribution is 2%, and the full width is 9%.

4.2. Temperature dependence

In order to estimate the temperature dependence of the light pulser prototype components, we performed measurements with two different temperatures inside the case, 27°C and 45°C. During these measurements the temperature of the PMT remained stable, and we compared the signals measured by this PMT. The mean ADC count of the blue LED signal distribution became smaller by 11.5% when the temperature increased from 27°C to 45°C. Assuming that the temperature dependence is linear, the coefficient is estimated as -0.64% at 27°C. The same analysis was done for the same LED signals measured by the photodiodes. We averaged between the results of measurements performed by each photodiode and obtained the temperature coefficient of the system blue LED pulser - photodiode is equal to -0.60%/°C. This means that photodiodes have their own temperature coefficient about 0.04%/°C in the region of 455 nm wavelength. The measured temperature coefficient of the red LED pulser is -1.0%/°C, and that of the photodiodes in the red region is 0.2%/°C at 27°C. The obtained results show that to keep a stability of the whole system at the level better than 0.2% we should reduce the temperature variation near the LEDs and the photodiodes down to 0.2°C.
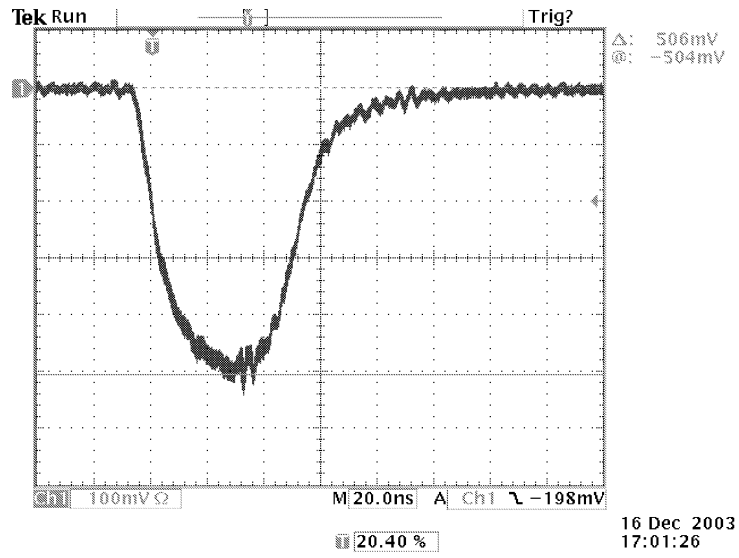
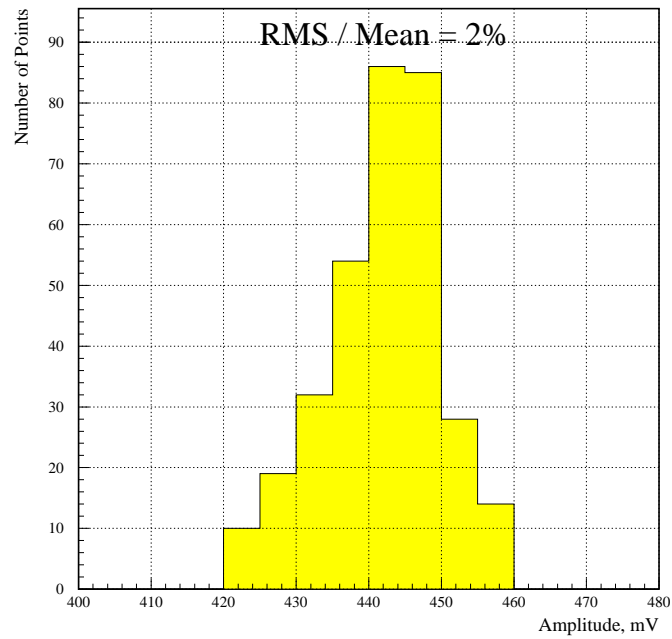Figure 3.   Blue LED signal at the anode of the PMT.

Figure 4.   Uniformity of the light distribution over the output window of the light mixer.

4.3. Long-term stability

To evaluate stability of the light pulser prototype we collected data continuously over one week. In these measurements, the DAQ recorded the following information every 9 seconds: 10 pulse heights from each LED detected by the photodiodes and by the PMT as well as the temperature data. For the analysis, we calculated mean values of signals accumulated over consequent 20 minute time intervals and formed their distributions. The r.m.s. of such distribution characterizes the stability of the given signal over the period of measurements.

Fig. 5 shows a variation of room temperature and temperature in the region of LED's over one week. We can see that temperature of LED's was stable within 0.1°C while the change of temperature outside the case achieved 2°C.

The dependence in time of blue and red LED signals detected by one of the reference photodiodes over one week of measurements is shown in Fig. 6(a) and (b) respectively. Normalized distributions that allow to evaluate stability of the whole system, i.e. the LED pulsers and the photodiode, are given in Fig. 6(c) for blue and 6(d) for red LEDs. The r.m.s. of these distributions, expressed in percent, are 0.05% and 0.04%. As expected, outside temperature variation didn't affect the performance of the prototype.
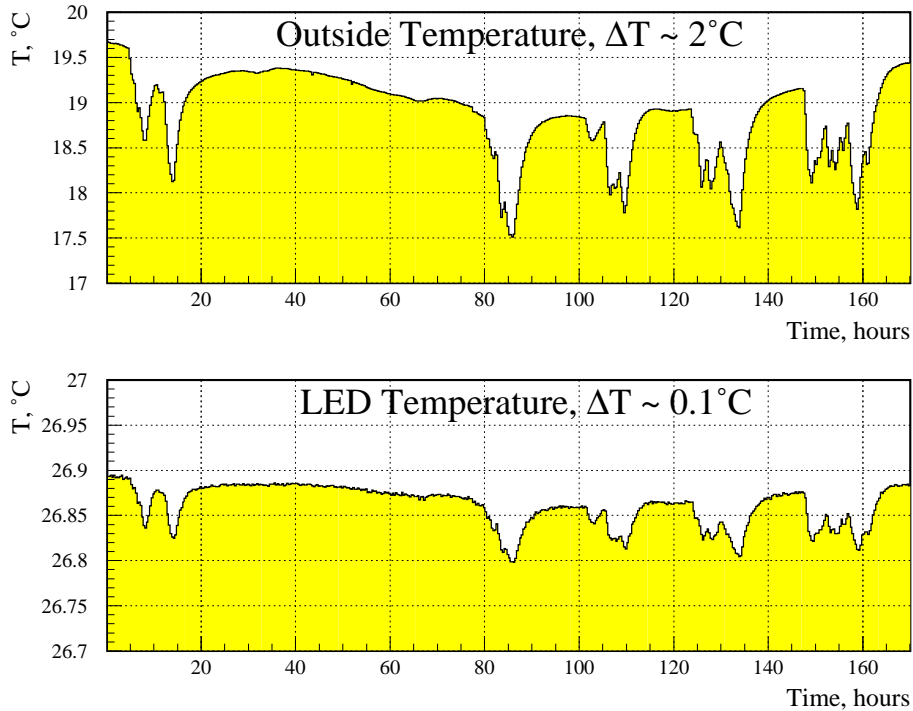

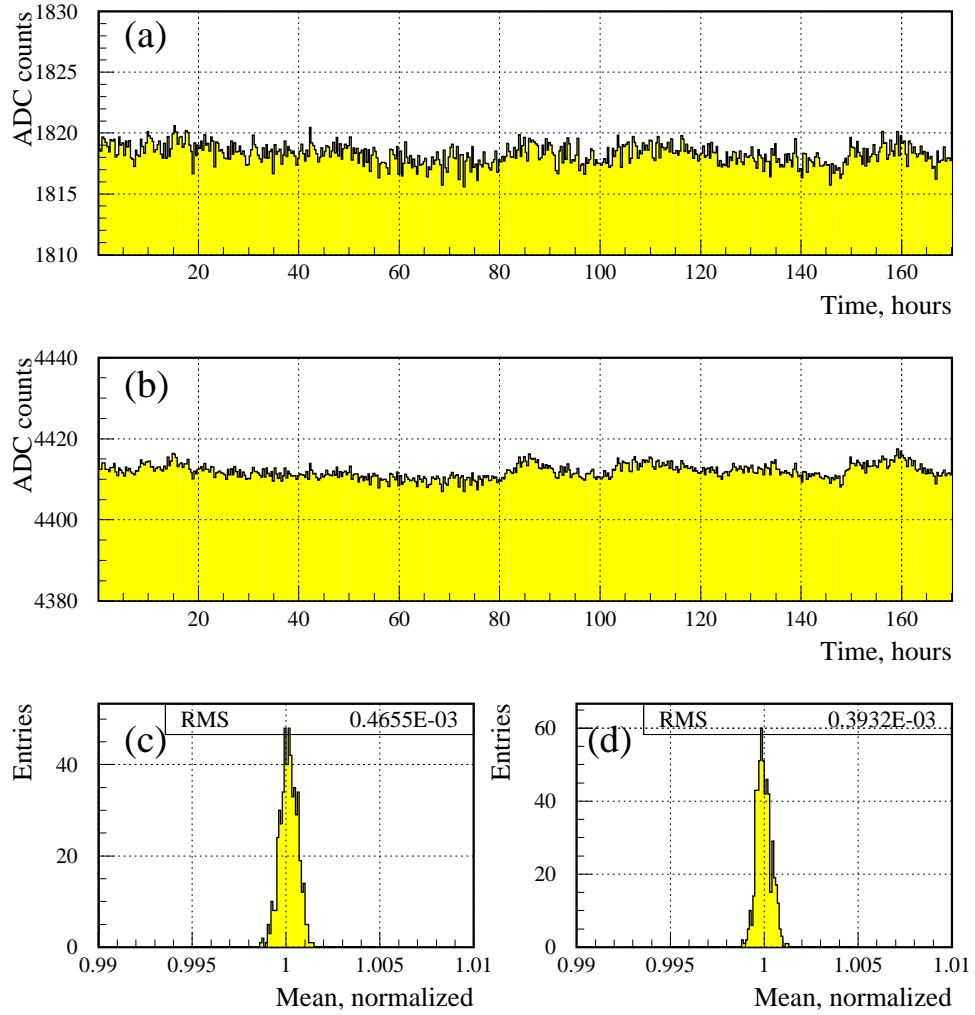Figure 5. Temperature variations during the prototype stability test.

Figure 6. Stability of the LED pulser prototype: (a), (b) — dependence in time of blue and red LED signals respectively detected by one of the photodiodes over one week of measurements; each entry is a mean value of amplitude distribution collected over 20 min; (c), (d)— distributions of mean values; r.m.s. characterizes stability of the system over one week.

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5. Summary

We have developed the LED-based monitoring system for the electromagnetic calorimeter that uses PWO crystals coupled with PMTs. The expected conditions and demands of the BTeV project were taken into account. The prototype of the light pulser based on the blue and red LEDs and reference silicon photodiodes has been designed, assembled and succesfully tested in the laboratory.

The prototype module is capable to provide continuous monitoring of the PMTs gain variation and crystals light output change due to the beam irradiation for about 3000 cells of the EMCAL. The maximum difference of the light pulses intensity in different channels is 9%. The prototype stability was estimated over the time period of one week. We found that the blue LED pulser is stable to 0.05% and the red LED pulser is stable to 0.04%, within one week of continuous operation. This exceeded the requirements of the project.

This highly stable monitoring system combined with in-situ calibration of the EMCAL would ensure the superb intrinsic resolution of the lead tungstate crystal calorimeter over the whole period of its operation.

Acknowledgements

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