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Calibration and monitoring for crystal calorimetry

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Abstract

Crystal calorimetry provides excellent energy resolution in high energy and nuclear physics. The light output of heavy crystal scintillators, however, suffers from not negligible damage in radiation environment. A precision calibration and monitoring thus is crucial for maintaining crystal precision in situ. The performance of calibration and monitoring approaches used by *BaBar*, CLEO and L3 experiments are presented. The design and construction of a laser-based light monitoring system for CMS PWO calorimeter is also discussed.

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Keywords: Lead tungstate; Crystal; Scintillator; Radiation hardness; Light output

1. Introduction

Total absorption shower counters made of inorganic scintillating crystals have been known for decades for their superb energy resolution and detection efficiency. In high energy and nuclear physics, large arrays of scintillating crystals have been assembled for precision measurement of photons and electrons. Crystal calorimetry provides excellent physics discovery potential. All known scintillating crystals, however, suffer from radiation damage. The main damage effect is radiation induced absorption caused by color center formation, which reduces crystal's light attenuation length, and hence the light output [1]. Fig. 1 shows light output degradation at 2–3% level per year observed in the *BABAR* CsI(Tl) calorimeter [2]. Similarly, about 15% loss of light output in 12 years was observed in the CLEO CsI(Tl) calorimeter [3]. The degradation of L3 BGO crystals was observed to be about 7% in seven years [4]. A fundamental approach to address this degradation is to develop crystals of better quality.

Fig. 2 shows recovery of normalized light output following 2.5 krad irradiations for three BGO samples doped with different levels of europium (BGO1, BGO2 and BGO3), as compared to the undoped sample BGO0 [5], indicating significant

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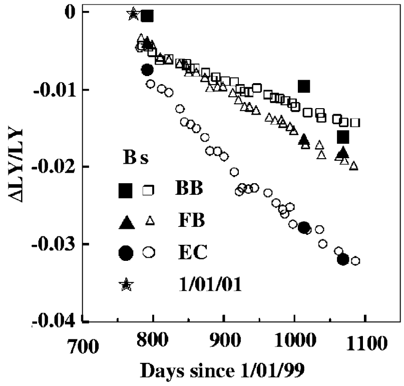

Fig. 1. Degradation of light output of the *BABAR* CsI(Tl) calorimeter in barrels (BB, FB) and endcap (EC) [2].

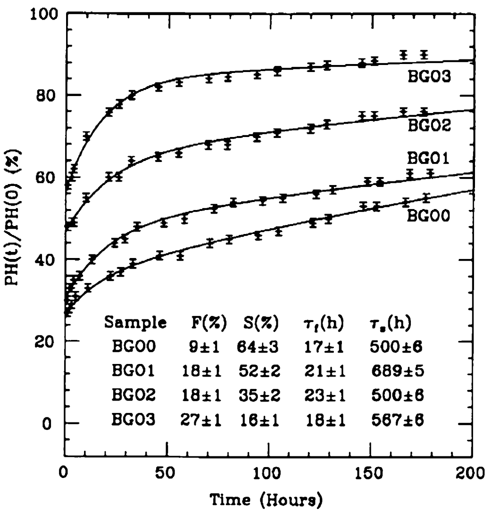

Fig. 2. Recovery of normalized light output is shown as a function of time after 2.5 krad irradiations for four BGO samples doped with different levels of Eu [5].

improvement in radiation resistance was achieved by the Eu doping. Similar improvements were achieved in CsI(Tl) [1] and PWO [1,6] crystals. It, however, is almost impossible to develop mass produced crystals with no residual radiation damage. Calibration and monitoring thus is crucial for maintaining the precision offered by crystal calorimetry in situ.

2. Calibration and monitoring in situ

Even all of the individual calorimeter cells (crystal, photo-detector, and readout chain) may be calibrated in a test beam the variation in response over time differs from one cell to the next. Calibrations in situ therefore are required to track down this evolution. The task of calibration can be divided into two parts: (1) finding the absolute energy scale of the calorimeter (absolute calibration) and (2) measuring the relative ratio between cells (inter-calibration). The precisions in both procedures affect the mean value of the measured energy, as well as the resolution.

Physics processes are used for calibration in situ since it covers the right energy range and it does not require additional hardware. Commonly used physics processes include single electrons or photons of known energy and electron or photon pairs of a known invariant mass.

Dedicated calibration source and light pulse based monitoring apparatus are used. A monitoring device measures relative transmittance variation, which can be used in tracking relative calibration variation since radiation damages in most crystals do not affect scintillation mechanism [1]. The L3 BGO calorimeter is equipped with a Radio-frequency Quadrupole (RFQ) based calibration system [7] and a xenon lamp based monitoring system. A radioactive photon source at 6.13 MeV and a monitoring light source are also used by the *BaBar* CsI(Tl) calorimeter [8].

Fig. 3 shows installation of the RFQ accelerator-based calibration system. The system consists of a 30 keV RF (2 MHz) driven H-ion source, a 1.85 MeV RFQ (425 MHz) accelerator, steering magnets, a beam neutralizer, a 10 m long beam pipe and a water-cooled Li target. 17.6 MeV photons are produced through a radiative capture of protons by the Li target, and are used as calibration source.

Fig. 4 shows normalized energy spectra of Bhabha electrons measured by L3 BGO calorimeter at LEP II and I by using FRQ calibration. Taking into account the intrinsic energy spread caused by radiative photons and temperature variations, the calibration precision is estimated to be better than 0.5% [7]. It is interesting to note

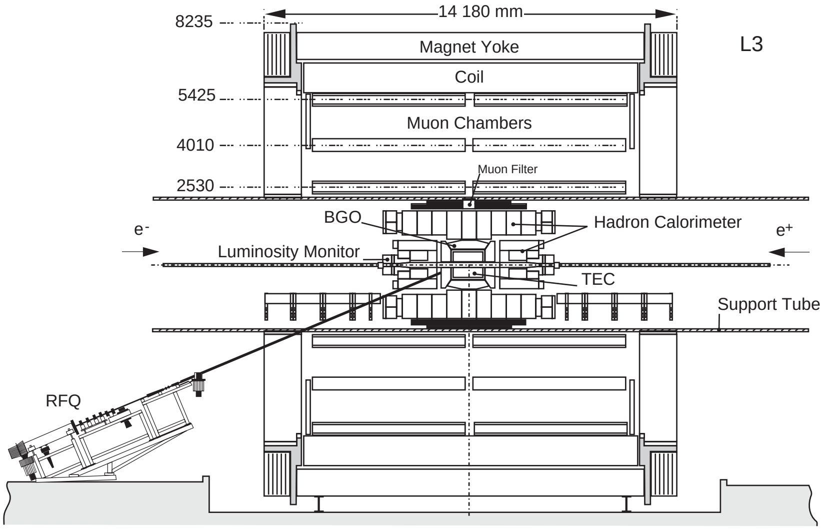

Fig. 3. Installation of the RFQ calibration system in the L3 detector at LEP [7].

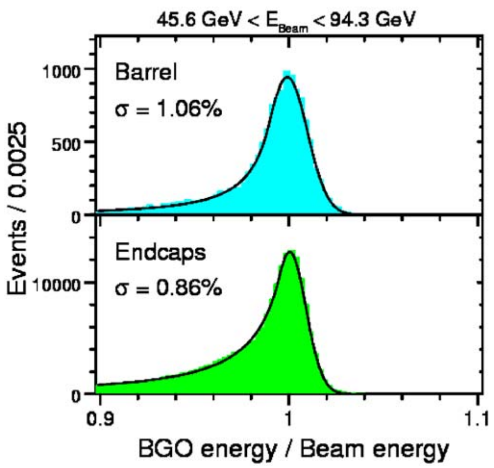

Fig. 4. Normalized Bhabha electron energy spectra measured by L3 BGO crystal calorimeter at LEP by using RFQ calibration.

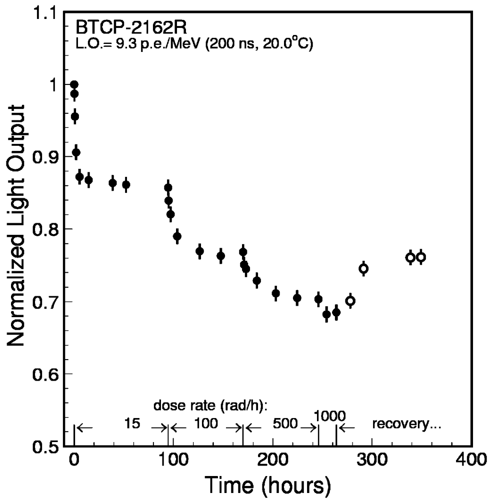

Fig. 5. Normalized light output of a PWO sample is shown as function of time during irradiation and recovery.

that a sub-percent precision can be achieved at high energies for mass produced BGO crystals.

3. Monitoring lead tungstate crystals

Because of its high density and fast decay time, lead tungstate (PWO) crystal has been one of the primary choices for crystal calorimeters in high energy and nuclear physics. After extensive R&D, current mass produced PWO crystals, however, still suffer from not negligible radiation damage [9]. PWO crystal's light output degrades under irradiation and recovers after, as shown in Fig. 5. The damage in PWO crystals is dose rate

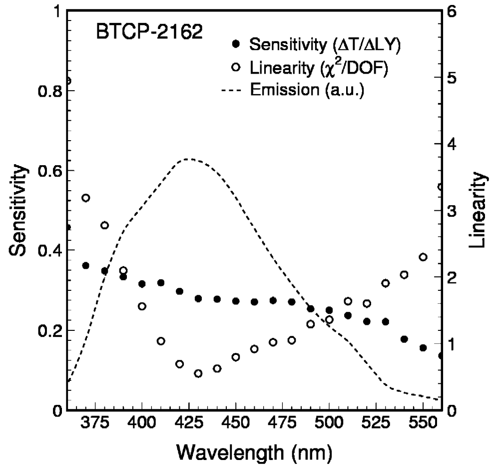

Fig. 6. Monitoring linearity and sensitivity are shown as function of wavelength for a sample [10].

dependent, which is due to color center formation and annihilation [1].

Since PWO crystal's light output degradation and recovery occur in a short time scale (hours), while calibration must be carried out in a long time scale (days or even weeks) with sufficient statistics, a light monitoring system is crucial. A laser-based light monitoring system is under construction by CMS. Fig. 6 shows monitoring linearity and sensitivity as function of wavelength measured by a test bench. The monitoring wavelength was chosen to be 440 nm for the best linearity and fiber transmittance [10].

The CMS ECAL monitoring light source uses three laser systems. Each laser system contains an Nd:YLF pump laser and a tunable Ti:S laser, as shown in Fig. 7. The pump lasers provide frequency-doubled pulse at 527 nm with intensity up to 20 mJ. The tunable Ti:S lasers provide pulse intensity up to 1 mJ at two wavelengths. The monitoring light source in operation consists of two running laser systems and provides 4 wavelengths: 440, 495, 709 and 796 nm. The third laser system (440 and 495 nm) is used as a spare to guarantee 100% availability of the 440 nm. The first laser system was installed at CERN in 2001 and has been used in beam test since then. The second and third laser systems were installed at CERN in 2003.

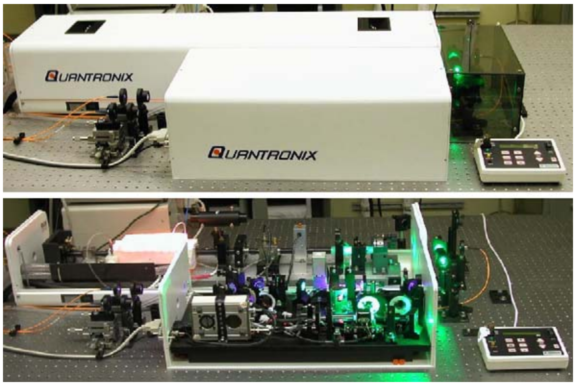

Fig. 7. A pair of monitoring lasers with covers closed (top) and open (bottom) [10].

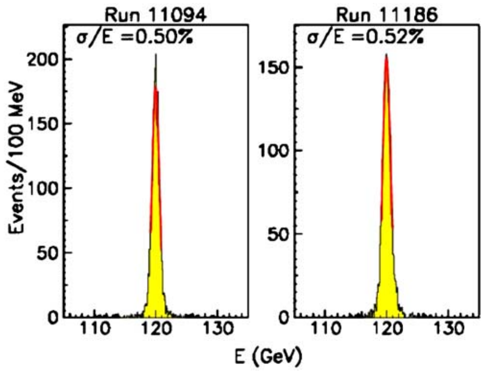

Fig. 8. Reconstructed energy spectra measured by PWO crystals before (left) and after (right) irradiation [11].

Fig. 8 compares energy spectra measured by a PWO test matrix before and after irradiation by electron beam. Despite 10% loss of light output, the reconstructed energy resolution is maintained at 0.5% for 120 GeV electrons by using light monitoring [11].

4. Summary

Because of the total absorption, crystal calorimetry provides good resolution for electron and photon measurements, and thus excellent physics potential. To address radiation damage in scintillating crystals, extensive R&D has been carried out to improve crystal radiation hardness. Mass produced crystals, however, may still suffer from not negligible radiation damage, which is to be taken care of by precision calibration and monitoring in situ. A light monitoring system is crucial to track evolutions of crystal transmittance when statistics for physics calibration is being accumulated. With well-designed calibration and monitoring approaches, precision crystal calorimetry in a radiation environment is possible by using mass-produced scintillating crystals with residual radiation damage.

Acknowledgments

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References

[1] R.Y. Zhu, Nucl. Instr. and Meth. A 413 (1998) 297.
[2] T. Hryn'ova, in: R.Y. Zhu (Ed.), Calorimetry in Particle Physics, World Scientific, Singapore, 2002, p. 175.
[3] B. Heltsley, http://www.lns.cornell.edu/~bkh.
[4] J. Fay, in: G. Barreira, et al. (Eds.), Calorimetry in High Energy Physics, World Scientific, Singapore, 2000, p. 212.
[5] Z.Y. Wei, et al., Nucl. Instr. and Meth. A 302 (1991) 69.
[6] E. Auffray, F. Cavallari, P. Lecoq, P. Sempere, M. Schneegans, Status of the PWO Crystal Production from Russia for CMS-ECAL, Nucl. Instr. and Meth. A 486 (2002) 111.
[7] U. Chaturvedi, et al., IEEE Trans. Nucl. Sci. NS-47 (2000) 2101.
[8] M. Kocian, in: R.Y. Zhu (Ed.), Calorimetry in Particle Physics, World Scientific, Singapore, 2002, p. 167.
[9] R.H. Mao, L.Y. Zhang, R.-Y. Zhu, IEEE Trans. Nucl. Sci. V-51 (2004) 1777.
[10] L.Y. Zhang, et al., IEEE Trans. Nucl. Sci. NS-48 (2001) 372.
[11] E. Auffray, et al., Nucl. Instr. and Meth. A 412 (1998) 223.