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Performance of the Monitoring Light Source for the CMS Lead Tungstate Crystal Calorimeter

Liyuan Zhang, David Bailleux, Adolf Bornheim, Kejun Zhu and Ren-yuan Zhu

California Institute of Technology, Pasadena, CA 91125, USA

Abstract

Light monitoring will play a crucial role in maintaining energy resolution for the CMS lead tungstate crystal calorimeter at LHC. In last several years, a laser based monitoring light source was designed and constructed at Caltech, and was installed and commissioned at CERN. This paper presents the design of the CMS ECAL monitoring light source and its performance during beam test. Issues related to the monitoring precision are discussed.

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1 Introduction

The main physics motivation for building the Compact Muon Solenoid (CMS) experiment at Large Hadron Collider (LHC) is to investigate the mechanism responsible for electroweak symmetry breaking. In the low mass range between 115 and 150 GeV the Higgs discovery potential in the $\gamma\gamma$ decay channel is directly related to the reconstructed mass width, or the energy resolution of the electromagnetic calorimeter (ECAL). The CMS lead tungstate ($PbWO_4$ or PWO) crystal ECAL has a designed energy resolution ($\sigma E/E$) of $\mathbf{2.5}\%/\sqrt{E} \oplus \mathbf{0.55}\% \oplus 0.2/E$ for the barrel and $\mathbf{5.7}\%/\sqrt{E} \oplus \mathbf{0.55}\% \oplus 0.25/E$ for the endcaps, where $\oplus$ stands for addition in quadrature and E is in GeV [1]. Test beams at CERN have shown that this energy resolution can be achieved by using mass-produced PWO crystals with APD readout [2].

Because of high energy and high luminosity at LHC the CMS detector will be operated in a severe radiation environment. The mass produced lead tungstate crystals are radiation hard to high integrated dosage, but suffer from a dose rate dependent radiation damage as shown in induced absorption [3]. Our previous studies concluded that the scintillation mechanism of PWO is not affected by radiation, and the loss of light output is due only to the radiation induced absorption.

Fig. 1 (left) shows no variation of excitation and emission spectra indicating no damage in scintillation mechanism. Radiation damage, however, is observed in formation of radiation induced color centers, as illustrated in the transmittance spectra shown in Fig. 1 (right). Because of the equilibrium between color center's formation process and its annihilation process, the level of radiation damage in PWO crystals is dose rate dependent, as shown in Fig. 2.

2 Specification to the Monitoring Light Source

A precise calibration *in situ* is a key in maintaining the precision offered by a crystal calorimeter. For the CMS PWO calorimeter, a light monitoring system is designed to measure variations of crystal's optical transmission and use that to project variations of their light output [4]. It injects light pulses produced by a laser system into each individual crystal via an optical fiber system organized in three levels [5]. An fiberoptic switch sends laser pulses to one of 80 calorimeter elements (72 half super modules in the barrel and 8 half Dees in two endcaps). A two level distribution system, designed and constructed by Saclay DAPNIA, is mounted on each calorimeter element and delivers laser pulses to each individual crystal. Combined with crystal response to physics events the monitoring system is expected to help provide calibration with a precision of 0.4%. The specification for the laser based monitoring light source is listed below [7].

- Two Wavelengths: one close to the emission peak which provides the best monitoring linearity for the PWO crystals, and the other provides a cross check.
- Spectral Contamination: $< 10^{-3}$;
- Pulse Width: full width at half maximum (FWHM) < 40 ns to match the ECAL readout;
- Pulse Jitters: < 3 ns for trigger synchronization to the LHC beam;
- Pulse Rate: $\sim$80 Hz, which is the maximum rate at which the 'spy mode' ECAL DAQ used for monitoring events can operate;
- Pulse Energy: 1 mJ/pulse at monitoring wavelength, corresponding to 1.3 TeV in dynamic range;
- Pulse Intensity Instability: $<$10%.

To track down variations of crystal light output caused by radiation damage and its recovery continuously, the monitoring system is required to be operational 100% of the time during the data taking [6]. To provide a continuous monitoring, about 1% of the 3.17 μs beam gap in every 88.924 μs LHC beam cycle [8] will be used to inject monitoring light pulse into crystals. The time needed to scan entire ECAL is expected to be less than 30 minutes [7].

3 Design of the Monitoring Light Source

The CMS ECAL monitoring light source consists of three laser systems, each with their own diagnostics, two fiberoptic switches, internal monitors and corresponding PC based controllers. Fig. 3 is a schematic showing the design of the monitoring light source and high level distribution system. As shown in this figure each laser system consists of an Nd:YLF pump laser (Fig. 4 back), its power supply and cooler unit and corresponding transformer, a Ti:Sapphire laser (Fig. 4 front) and its controller, and a NESLAB cooler for an LBO crystal in the Ti:S laser. Each pair of the YLF and Ti:S lasers and their corresponding optics are mounted on an optical table.

The choice of monitoring wavelength directly affects the monitoring sensitivity and linearity [4]. Fig. 5 shows the monitoring sensitivity (the slope of a linear fit to ΔT/T versus ΔLY/LY, where T and LY refer to transmittance and light yield respectively) and the linearity (χ^2/DoF of the fit) as a function of the monitoring wavelength for a PWO sample. Also shown in the figure is the PMT quantum efficiency weighted radio luminescence. The higher monitoring sensitivity at shorter wavelength is understood because of the lower initial transmittance as compared to that at the longer wavelength. The best linearity around the peak of the radio luminescence is understood by two radiation-induced color centers peaked at the two sides of the luminescence peak with different damage and recovery speed [4]. Based upon this result, 440 nm (blue) was chosen as the monitoring wavelength. In addition, 796 nm (infrared) is used to monitor independently the gain variations of the readout electronics chain from APD to ADC.

All three pump lasers are model 527DQ-S Q-switched Nd:YLF laser, which is a commercial product by Quantronix Inc. [9]. It provides frequency doubled laser pulse at 527 nm with a pulse intensity up to 20 mJ at a repetition rate up to 1 kHz. All three Ti:S lasers are custom made Proteus UV(SHG) laser from Quantronix, which provides pulse intensity up to 1 mJ at repetition rate up to 100 Hz [7]. Two wavelengths are available for each Ti:S laser, which is tunable by choosing appropriate built-in filter. Each set of lasers has a main output and a diagnostic output. The diagnostic output is further split to two fibers by using a fiber splitter. One output goes to a monochromator for wavelength spectrum monitoring, while the other goes to a digital scope which samples pulse energy, width and timing at a rate about 1 Hz. The histograms and history of laser pulse energy, FWHM, timing and wavelength spectra obtained by the digital scope and the monochromator are stored in the computer.

As shown in Fig. 3, the monitoring light source in operation consists of two laser systems, so that a total of 4 wavelengths, 440 (blue), 495 (green), 709 (red) and 796 (infrared) nm, are available by using a 2×1 optical switch [10]. The output of this switch goes to a monitoring box, which measures laser pulse energy and FWHM by using an Acqiris DP210 digitizer card sampling each laser pulse at 2 GS/s and provides a logarithmic attenuator and a linear attenuator for the main laser output. The output of the monitoring box is distributed via a 1×80 fiberoptic switch to 80 calorimeter elements through 150 m long quartz fibers. The histograms and history of pulse energy and FWHM are also stored in the computer. The third laser system is a spare laser, which also provides 440 (blue) and 495 (green) nm to guarantee 100% availability of the main monitoring wavelength at 440 nm even during laser maintenance [6]. This spare laser system has its own control, so can be used independently.

4 Performance of the Monitoring Light Source

The first blue/green laser system and its corresponding diagnostics were installed and commissioned at CERN in August, 2001 [11], and was used in beam tests since then. In August 2003, the IR/red and the second blue/green laser system was installed and commissioned at CERN [12]. All three laser systems are housed in a laser barracks with air condition and safety features. Fig. 6 shows a typical history of the laser pulse intensity in a 19 day run during beam tests at CERN. All four wavelengths are used. Laser pulse intensity scans were carried out to test the linearity of the readout electronics.

The short term stability of the laser system, obtained in typical 30 minutes, is at a level of 1% to 2%. Fig. 7 and 8 show laser pulse energy and FWHM distributions respectively obtained for four wavelengths in 25 h runs, indicating that the long term stability of the pulse energy and FWHM width are at 3% level for the blue and IR, and about 7% for the red and green. This difference of stability is well understood. Since the Ti:S emission is peaked at 800 nm with a FWHM of $\sim$180 nm, its intensity, and thus stability, at 709 and 495 nm off the peak emission is limited.

Fig. 9 is a comparison of laser pulse intensity measured by ECAL readout and laser internal monitor for laser pulses at 800 nm, showing a good consistency. The data in this plot are presented without any reference and corrections. A stability at 1% level is achieved in this period of 6 days with some variations indicating temperature effect since both laser pulse intensity and width are known to be temperature dependent [13]. Following this observation and some degradation of laser optics observed during test beam running, a rigorous environmental control is planned to be implemented by using portable clean room facilities [13].

The laser based monitoring system was used to follow variations of PWO crystal transmittance in beam tests at

CERN. Fig. 10 shows 120 GeV electron and 440 nm laser data collected during a beam test when PWO samples were bombarded with electrons to simulate the LHC environment. The damage and recovery processes are clearly seen in the figure. The slope between variations of light output and transmittance observed in these processes are consistent.

5 Summary

In the last several years, a laser based monitoring light source was designed and constructed at Caltech, and was installed and commissioned at CERN. The performance of this system exceeds the original design specification. While detailed study is under way to understand ultimate performance of this monitoring system and its systematic effects, initial application in beam tests at CERN indicates that this laser based monitoring system will play a crucial role in maintaining the precision of PWO crystal calorimeter *in situ* at LHC.

Acknowledgments

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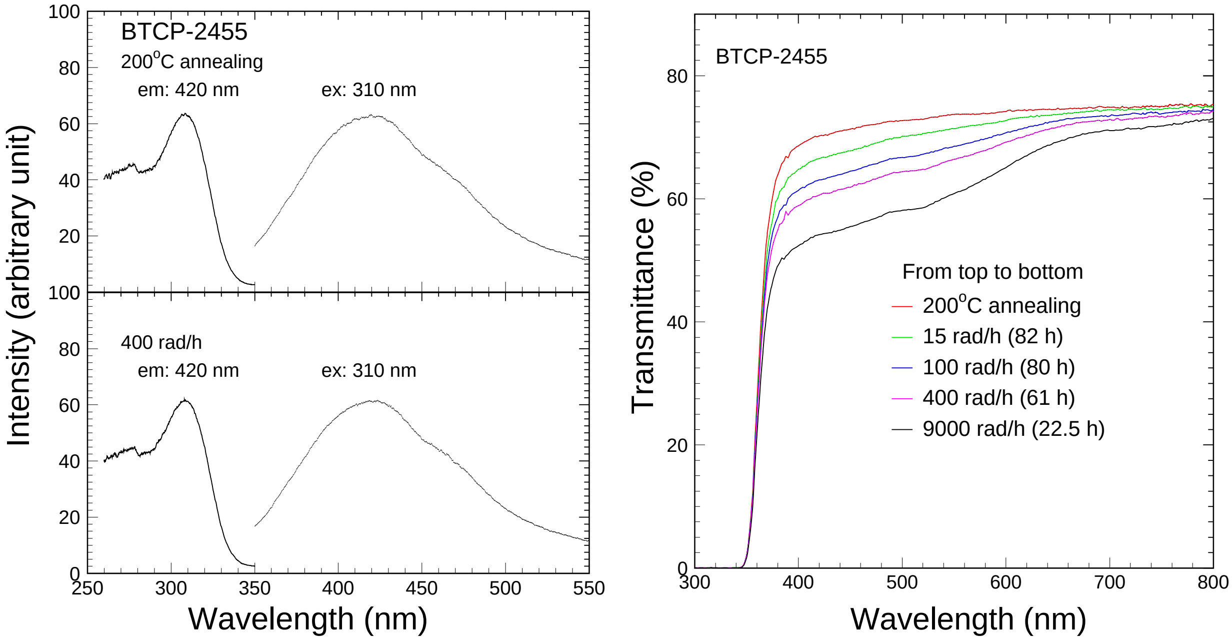

Figure 1: The excitation and emission spectra before and after irradiation at 400 rad/h (left) and the transmittance spectra at equilibrium under irradiations of several dose rates (right) are shown as function of wavelength for a PWO sample.

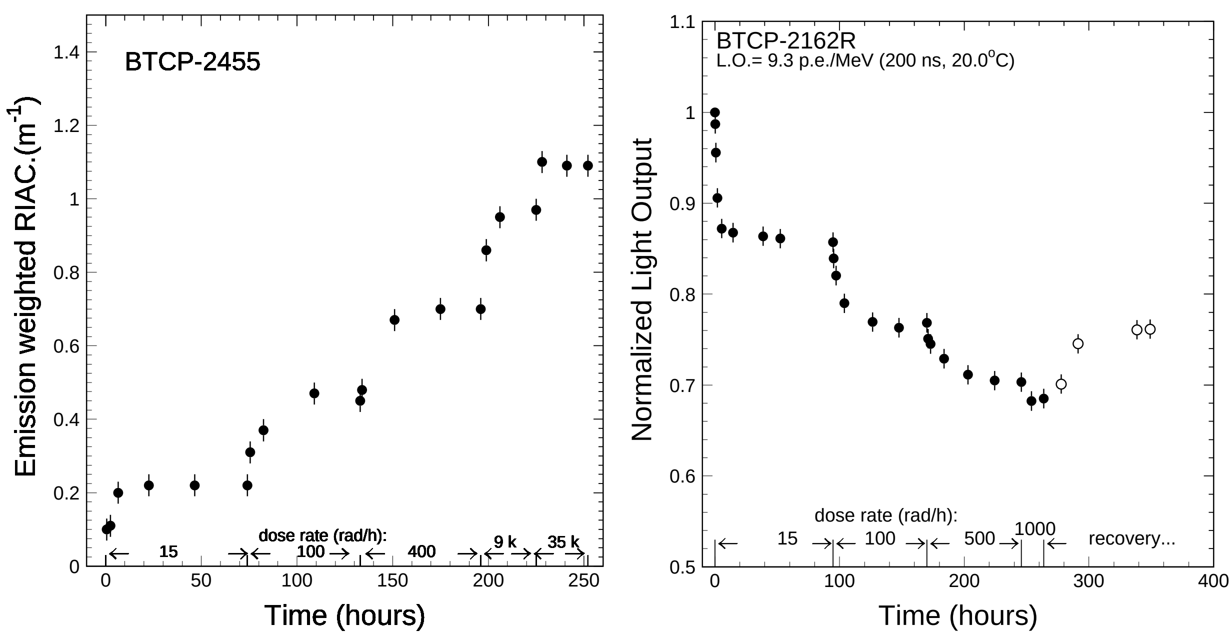

Figure 2: The damage history of the emission weighted radiation induced absorption coefficient (RIAC, left) and the light output (right) are shown as function of time for two PWO samples.

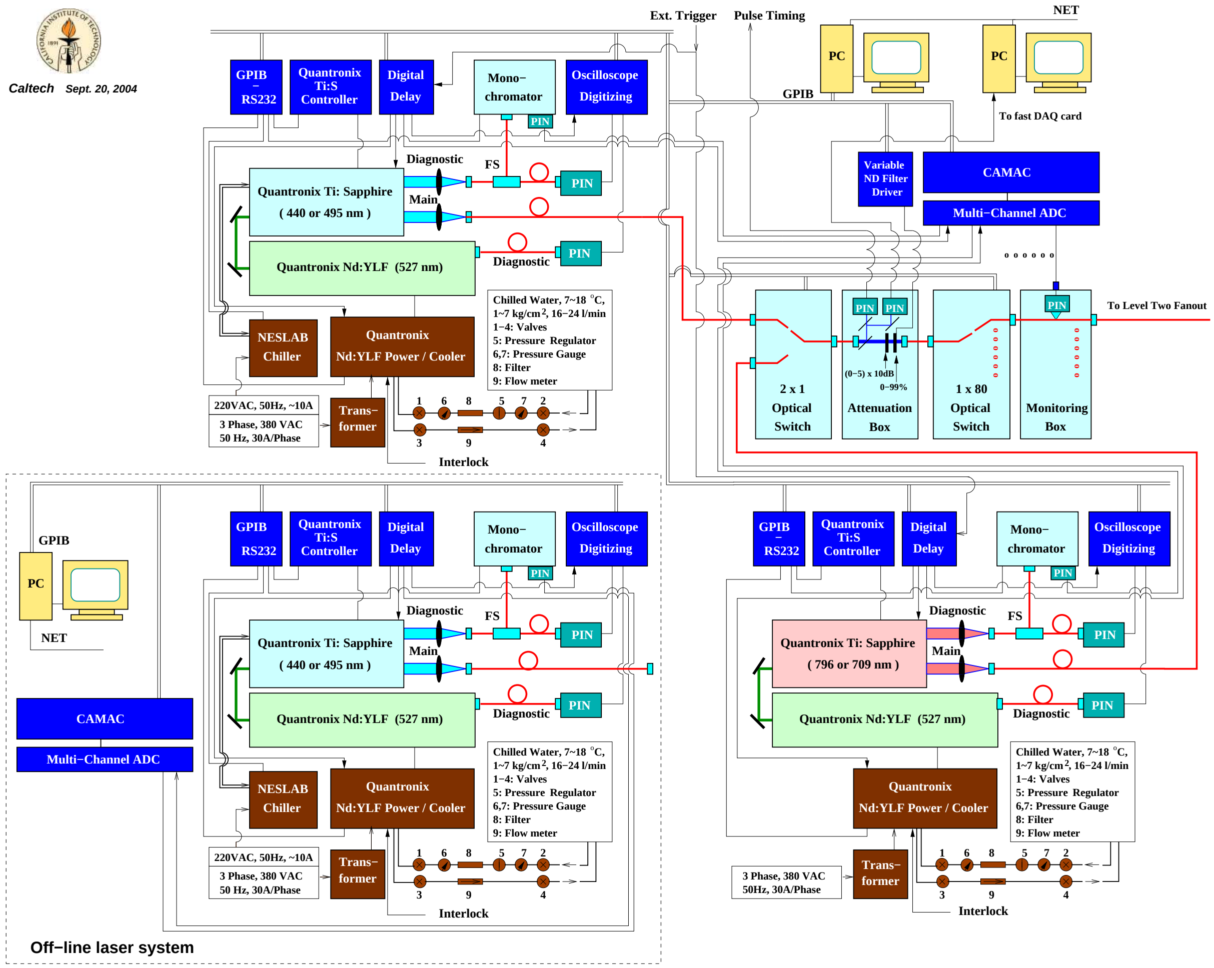

Figure 3: A schematic showing the design of the laser based monitoring light source and high level distribution system.

Figure 4: A photo of the Quantronix laser system showing the Nd:YLF pump laser (back) and the tunable Ti:S laser (front).

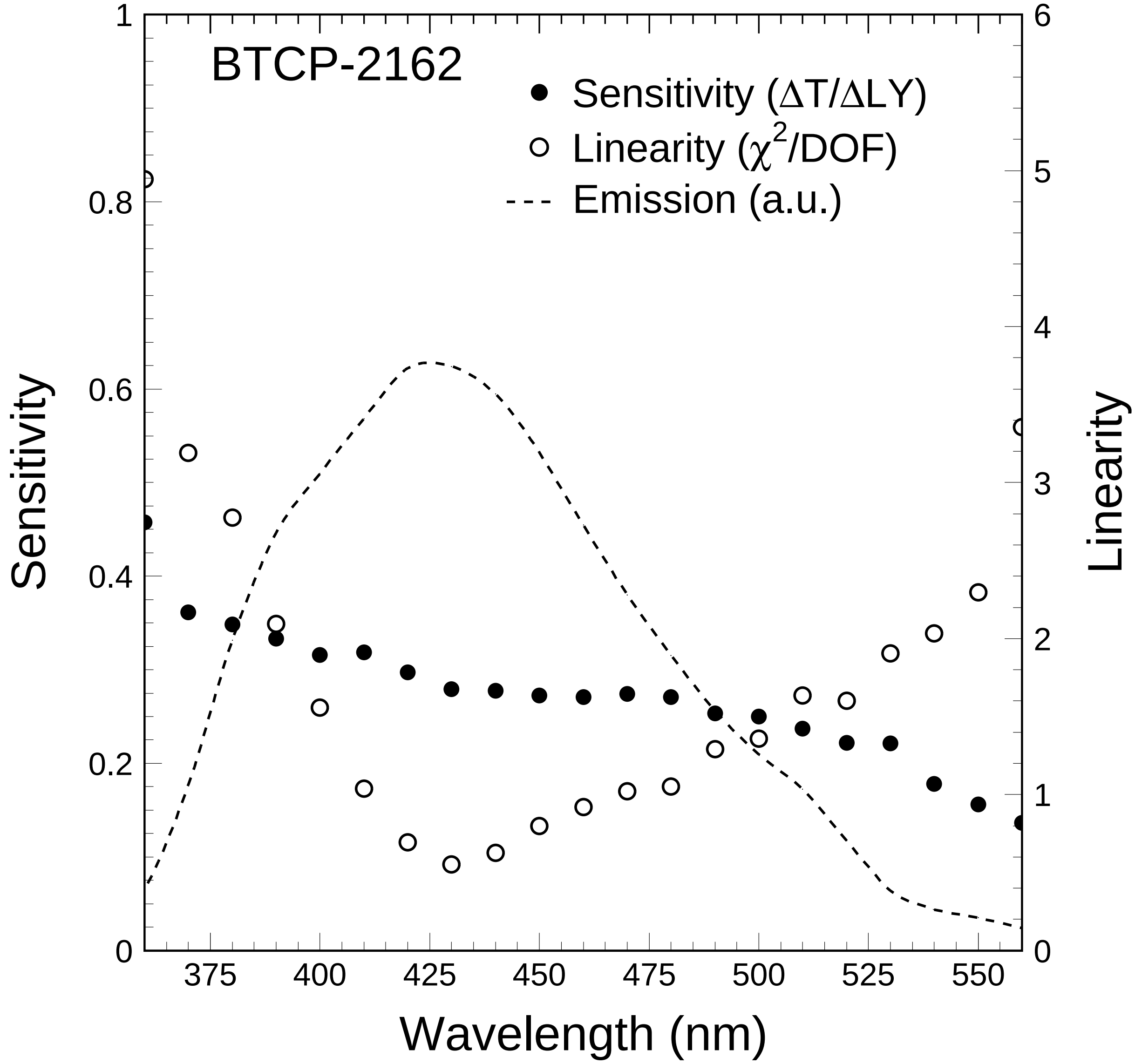

Figure 5: Monitoring sensitivity, linearity and emission spectrum are shown for a PWO sample.

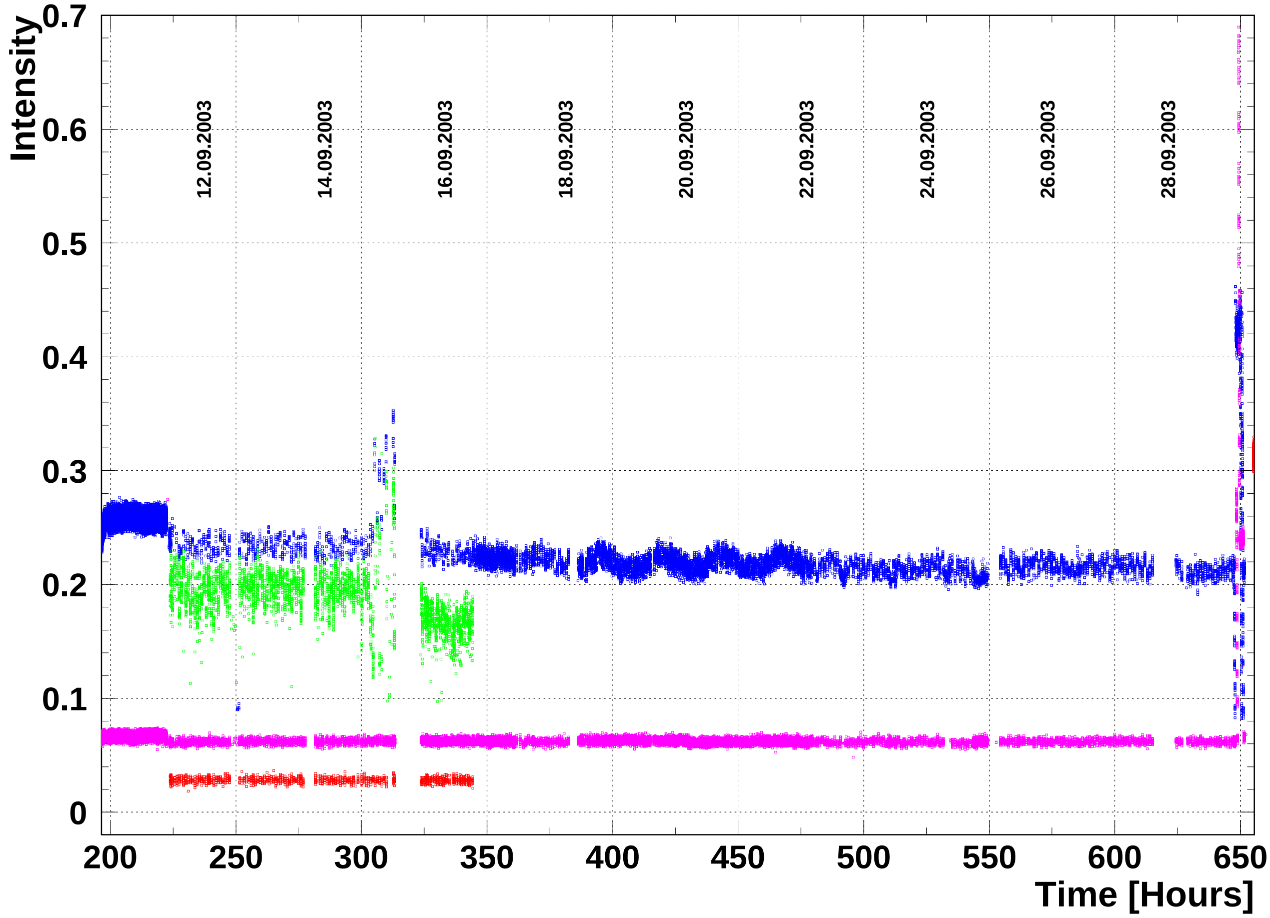

Figure 6: Laser pulse intensity is shown as function of time (h) during a 19 day period in a beam test at CERN, where blue, green, pink and red represent laser pulse energies at 440, 495, 709 and 796 nm respectively. Vertical spreads in the middle left (320 h) and right (650 h) are laser pulse energy scan runs for electronics test.

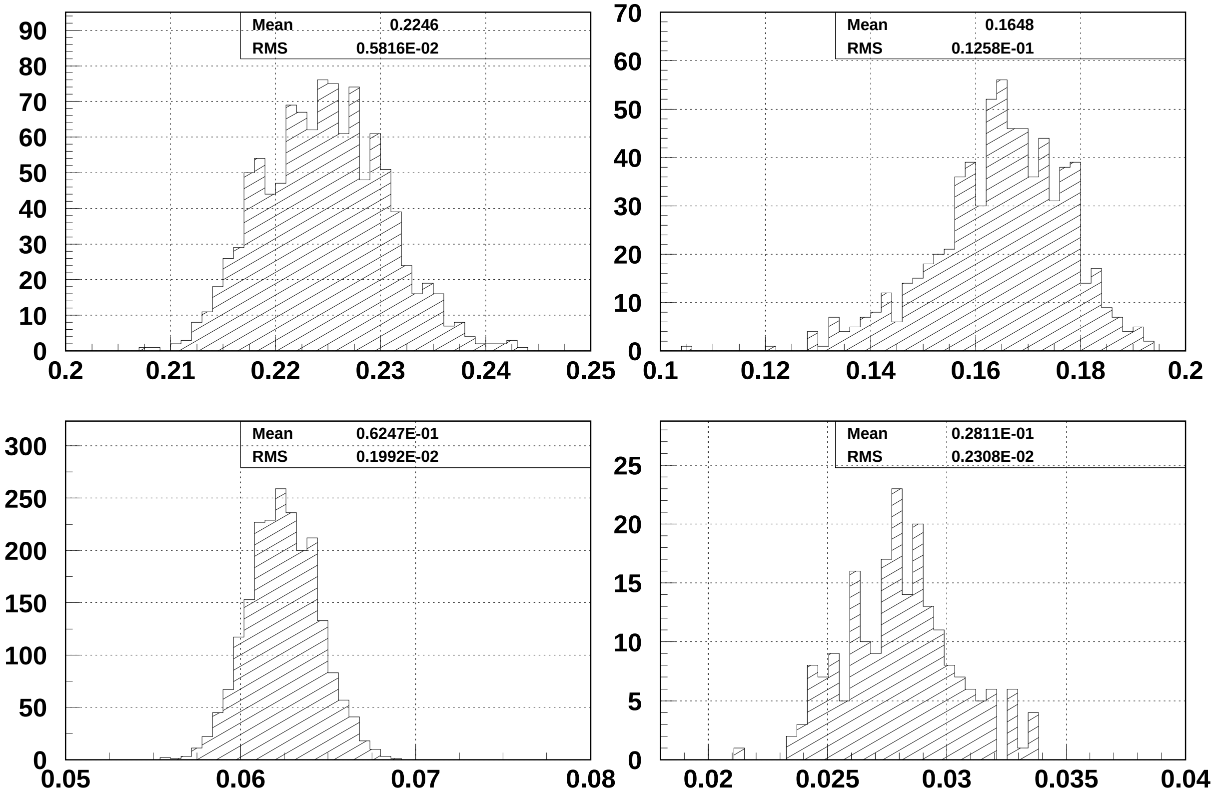

Figure 7: Distribution of laser pulse energy obtained in 25 hours for four wavelengths.

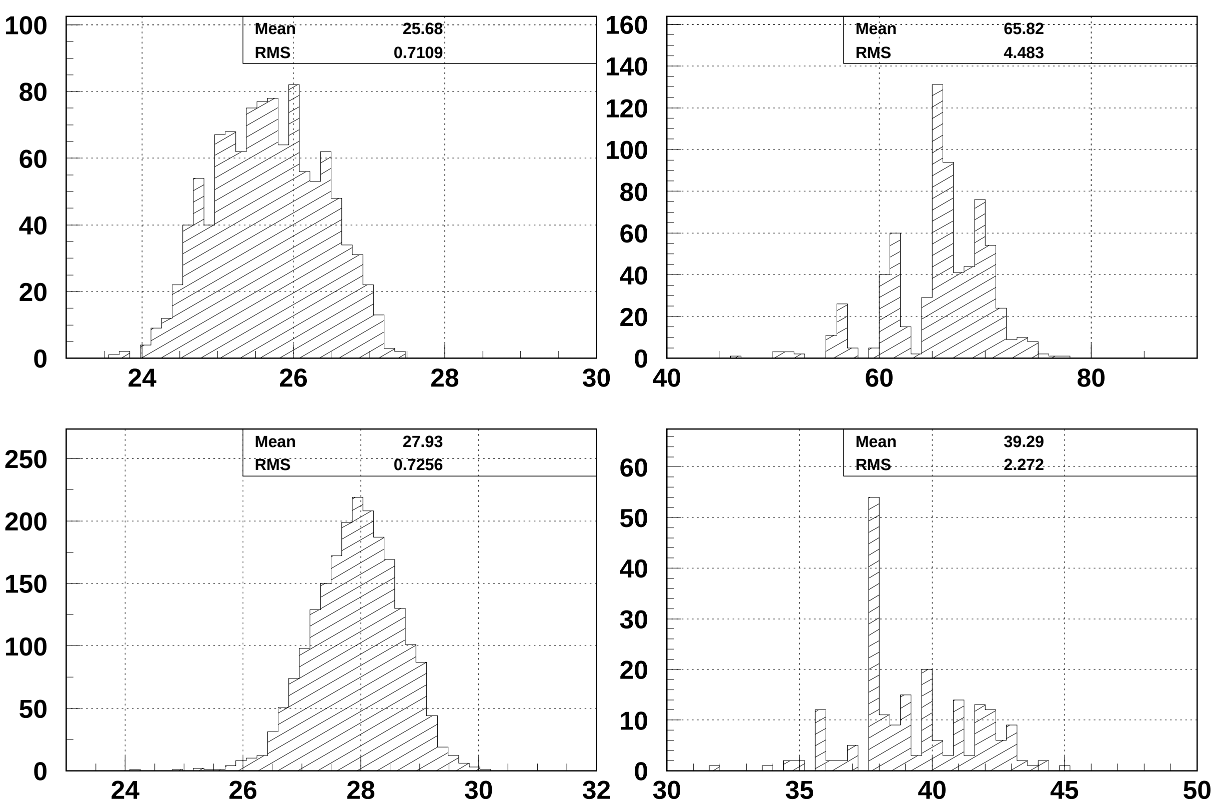

Figure 8: Distribution of laser pulse width obtained in 25 hours for four wavelengths.

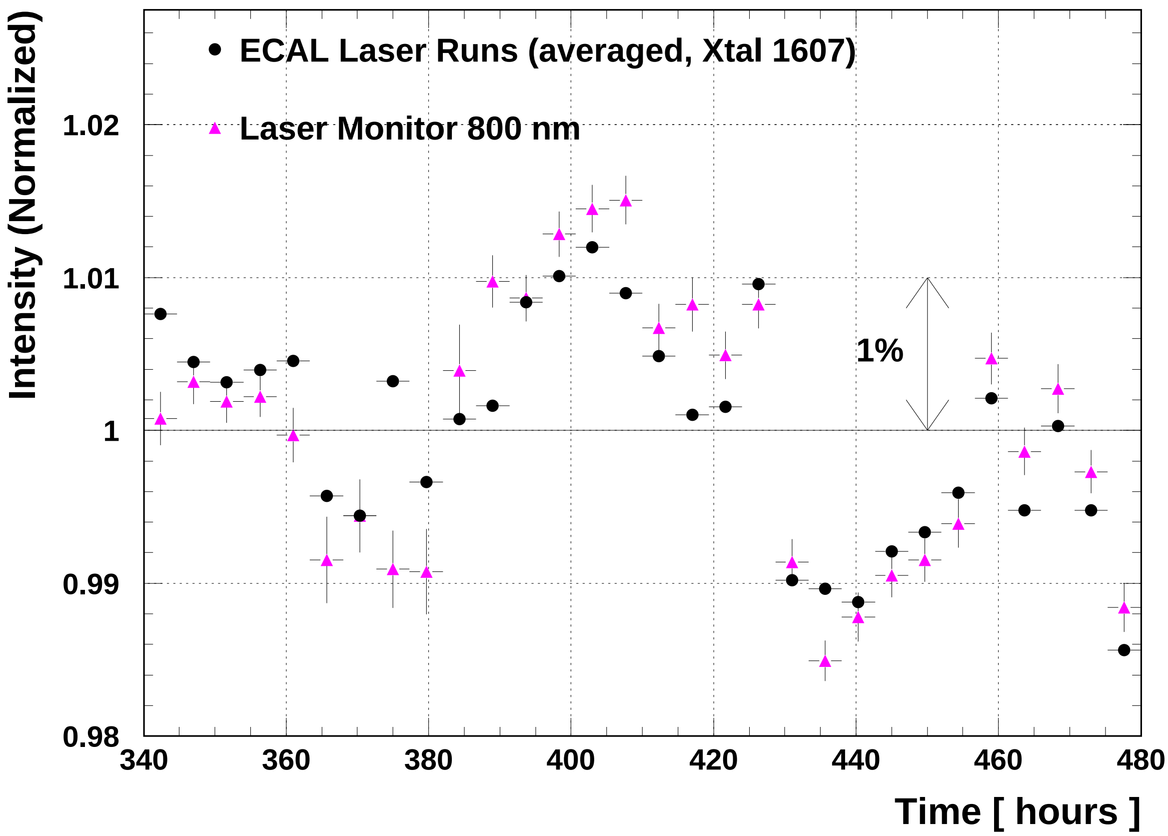

Figure 9: A comparison of laser pulse intensities measured in 6 days by ECAL APD readout (black) and laser internal monitor readout (red).

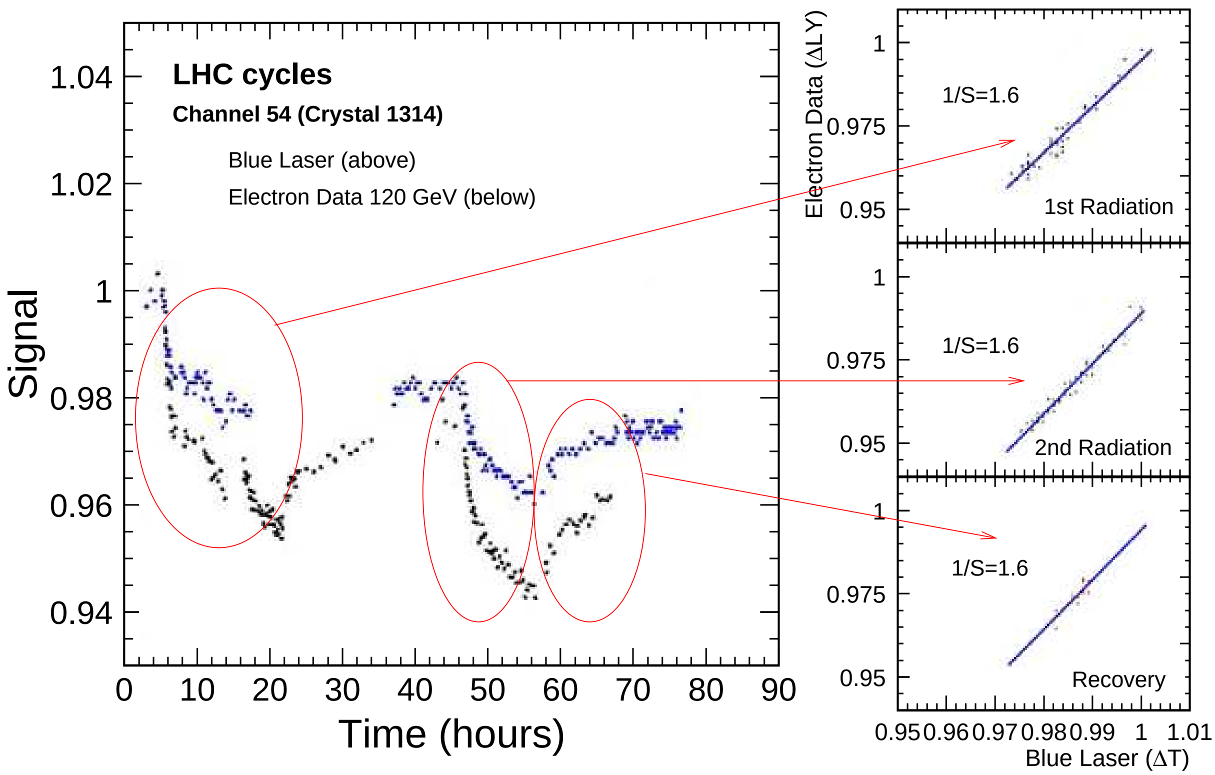

Figure 10: History of 120 GeV electron (black) and 440 nm laser (blue) data are shown as function of time during an irradiation beam test. Three expansions at right show the same linearity between electron and the monitoring signals.