ECAL
LASER MONITORING SYSTEM

OVERVIEW

DRAFT

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1 Introduction

We report on the multiple wavelength laser monitoring system designed for the CMS lead tungstate ($PbWO_4$) crystal calorimeter read-out with avalanche photodiodes (Barrel calorimeters) and vacuum phototriodes (End Cap calorimeters). The system operates in continuous measurement cycles to follow each crystal's evolution under irradiation and recovery periods foreseen during operation at the LHC.

Light monitoring will play a crucial role in maintaining the energy resolution of the CMS lead tungstate crystal electromagnetic calorimeter (ECAL) *in situ* at LHC.
Lead tungstate crystals were chosen for 75 848 channel electromagnetic calorimeter (ECAL) currently under construction for the Compact Muon Solenoid (CMS) experiment at the CERN LHC. This choice was based upon the crystal's high density and the intrinsic radiation hardness of the scintillation light mechanism. The scintillation signal S_i for a single channel (*i*) at a given emission wavelength λ in such a crystal calorimeter can be factorized approximately as follows:

$$S_i(E, \lambda) = [N(E) \cdot LY_i(\lambda)] \cdot Tr_i(\lambda) \cdot [A_i \cdot QE_i(\lambda) \cdot M_i(\lambda)] ,$$

Where:

N(E):	shower deposition	A:	geometrical acceptance
LY:	scintillation light yield factor	QE:	quantum efficiency
Tr:	optical transmission	M:	gain of the photodetector

The first term is unaffected by irradiation at LHC, and the third term can be controlled by designing radiation hard photodetectors and by measuring the electronic gain. The optical transmission, however, is a critical issue for these crystals, since light transmission at the scintillation wavelengths is affected by the production of color centers under electromagnetic irradiation. Furthermore, the annealing of these color centers at room temperature leads to a transmission recovery. Light transmission at any moment of time is the result of equilibrium between the rates of color center production and annealing. Crystals produced for ECAL are the result of a long R&D process to optimize doping and production stoechiometry to improve radiation hardness, thereby reducing the scale of the variations in light transmission to less than 6 % under LHC conditions (γ irradiation dose rates of 0.15 Gy/h at luminosities of 10^{34} cm^{-2} s^{-1}).
A critical issue in the performance of such a large system is the cell-to-cell uniformity. The energy resolution in the reconstruction of the Higgs two-photon decay is seriously degraded if the light transmission term is uncertain at the few % level. Final calibration of the ECAL will be achieved using physics events collected over days or weeks, depending upon the calibration process, but the energies need to be corrected for the short-term transmission variations. The goal of the system described in this paper is to achieve ≤ 0.5% relative inter-calibration with respect to the non-irradiated crystal transparencies and ensure long term stability (≤ 0.15% drift/month) in the transmission term over the nearly 80 000 channels of the full ECAL. The independent issues of precision and quality control have been addressed at each step of the systems conception and production.

Two options have been used elsewhere for light transmission measurements in large calorimeter systems: radioactive sources or external light injection. Radioactive sources are interesting in that they monitor the product of the light yield and transmission terms. Unfortunately, the relatively high noise level ~ 40 MeV of the ECAL Barrel avalanche photodiode (APD) and its associated electronics did not allow such a solution. Previously designed external light injection systems have used either stable light emitting diodes LED, which were too weak for the CMS application far within a 4 Tesla solenoid, or laser injection systems, which had sufficient power but had not achieved a precision ≤ 1.5%. We have followed this last approach, placing both a light-mixing step and a stable reference monitor sufficiently close to the final light injection at the crystal level to achieve a substantial increase in precision. The use of a laser monitoring system allows frequent (every ~20 min) *in situ* measurements of each crystal's light transmission, thereby following the damage and recovery during the physics data taking periods. The transmission results can then be used to correct raw energy deposits measured in the calorimeter in the same time intervals. Test beam studies at CERN have demonstrated the feasibility of maintaining energy resolution with light monitoring.

In this paper, we report on the design, installation at the detector level, and performance of the CMS ECAL laser monitoring system. The system has been used during test beam studies of ECAL Barrel supermodules (assembly of 1700 crystals) starting in 2001. System was installed and commissioned at Cessy in 2007.

2 Specification of the monitoring light source

Monitoring system injects light pulses produced by a laser into each individual crystal via optical fibers.
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.

- Operation duty cycle: 100% during LHC data taking periods (expected to be about 5000 hours/year);
- Two operating wavelengths: 440 nm (near $PbWO_4$ emission peak) & 796 nm (for electronics cross-checks);
- Spectral Contamination: $<10^{-3}$,which was confirmed with a high resolution monochromator, Oriel MS257;
- Pulse Width: full width at half maximum (FWHM) < 40ns ns to match the ECAL readout;
- Pulse Jitters: < 4 ns (24hours), <2ns (30min) for trigger synchronization to the LHC beam;
- Pulse Rate: ~80 Hz, which is allowed by ECAL DAQ;
- Pulse Energy: 1mJ at the source for a dynamic range up to 1.3 TeV in a crystal with 69 dB attenuation in the distribution system.
- Pulse Intensity Instability: < 10% of pulse energy;
- Clean room class: better than 10 000 to protect laser optics.
- Temperature stabilization: ±0.5° C and humidity <60%.

3 Monitoring light distribution system

3.1 Overview

The basic principle of operation is illustrated for the **ECAL Barrel** geometry in Fig. 1: laser pulses transported via an optical fiber are injected at a fixed position at the crystal's front face, the injected light is collected, as similarly done for scintillation light from an electromagnetic shower, using a pair of avalanche photodiodes (APD) glued to the crystal's rear face, and the pair are read-out in parallel with the front-end electronics chain. This design ensures that the crystal's optical transmission is measured in the region of interest, although the optical light path is somewhat different from that taken by scintillation photons. The underlying principle is similar for **ECAL End Cap**, however there the calorimeter design is based on identical 5x5 crystal units which does not permit front face injection; in this case, laser light is injected at a corner of each End Cap crystal's rear face, and the light is collected via a vacuum phototriode (VPT) glued on the crystal's rear face. Since the optical transmission depends upon light path, Tr(λ) differs between Barrel and End Caps.

In order not to interfere with ECAL performance during physics collisions at LHC, the laser pulses are injected during 3.17 µs gaps foreseen every 88.924 µs in the LHC beam structure, as shown in Fig. 2. The laser monitoring system independently measures the injected light for each pulse distributed to a group of typically 200 crystals using pairs of radiation hard PN photodiodes read-out via dedicated front-end electronics. The essential quantity used to make crystal optical transmission corrections is the ratio of the appropriate APD (or VPT for the End Caps) response normalized by the associated group's PN response. Altogether, 75 688 crystals, 61 200 for ECAL Barrel and 14 488 for the ECAL End Caps, will be monitored by the system at LHC, cycling continuously over the 88 calorimeter elements.

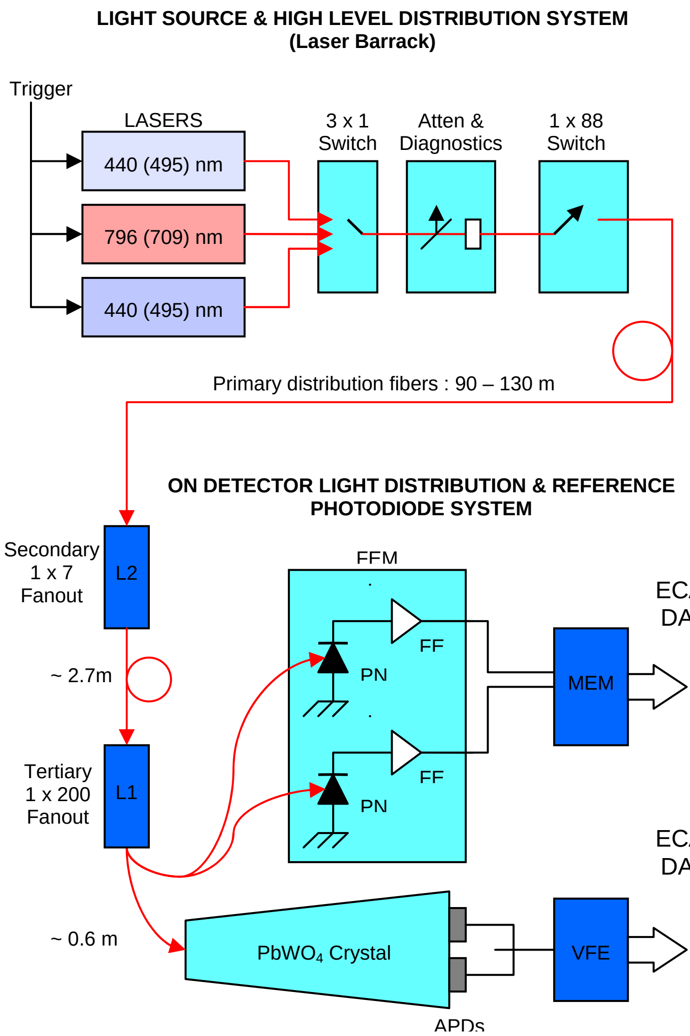


Figure 1: *Schematic view of the monitoring system in CMS-ECAL*

Light source and high level distribution system is described in section 4.

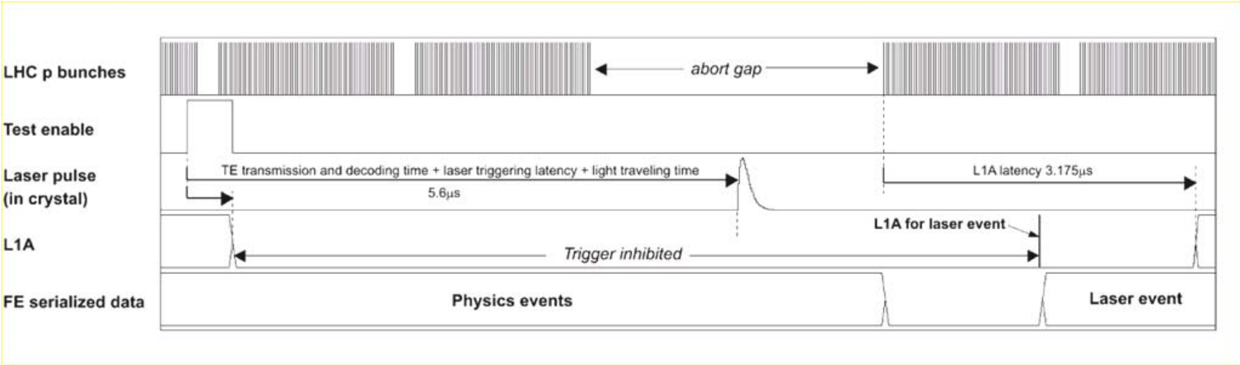


Figure 2: *Laser pulse timing diagram showing the LHC beam structure and the laser pulse within the 3µs abort gap (without physics collisions) foreseen every 88.924 µs cycle to allow for the rise time of the beam dump's fast kickers.*

3.2 Light distribution system

The monitoring light distribution system receives laser pulses from the fiber-optic switch at the source and injects them into individual crystals, front face (for barrel) or to the rear face (for end–caps) via **3–level distribution system**:
1) Primary fibers carry the pulses to the selected calorimeter element (e.g. ½ supermodule),
2) The second level (L2) distributes light inside a super–module to the third level half– in–phi modules,
3) The third level (L3) distributes light to crystals of a given half module (groups of 200 crystals).

The general layout of the distribution system is illustrated in Fig. 2 for an ECAL Barrel supermodule, and Fig. 3 for ECAL Endcap. The division of the supermodule into 2 calorimeter elements is apparent from this schematic: 2 monitoring units per Super-Module in the barrel and 4 per End-Cap Dee. In total, there are **88 monitoring units in CMS-ECAL** (72 in the barrel part and 16 in the end-cap one). These unit modularity will also be kept for the other measurements (pedestals and test-pulses).
The FEM units housing the pairs of reference PN photodiodes which monitor each fan-out are shown shaded. It should be recalled that a CMS ECAL Barrel supermodule is composed of 4 modules, starting from the interaction point (pseudorapidity $\eta = 0$): module 1 (500 crystals), module 2 (400 crystals), module 3 (400 crystals) and module 4 (400 crystals) located at the outer edge ($|\eta| = 1.479$). The primary fibers must access the element from the end of module 4 as shown in Fig. 4.
All of the distribution system components are mounted on the front face of the supermodule, sharing this space with the front cooling plumbing (note: throughout this paper the expression "front face" refers to the face closest to the LHC interaction point, through which particles enter the calorimeter). Individual crystals are accessed via slots in the front face.

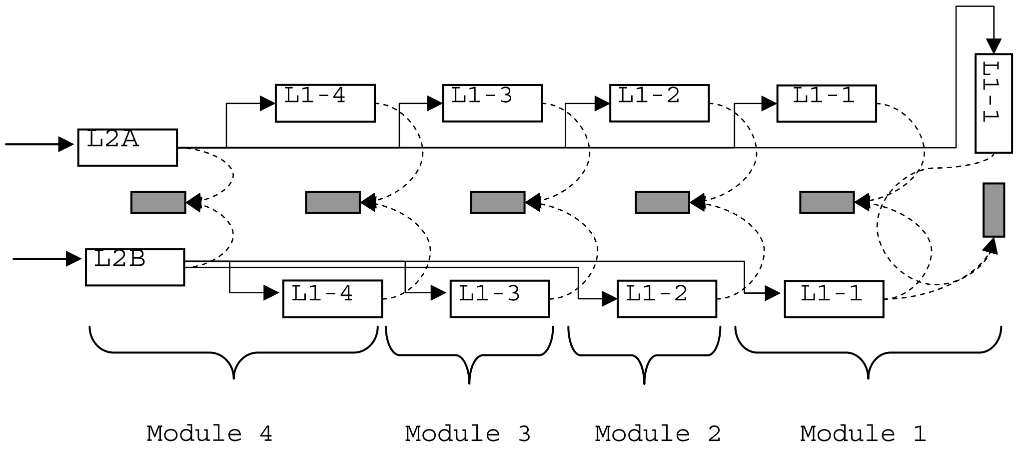


Figure 2: *Barrel laser monitoring regions. Laser pulses (entering at left) sent to either one of two secondary (L2) fan-outs L2A or L2B are distributed to crystals along left or right half of the supermodule's longitudinal axis via 4 or 5 tertiary fanouts located in each of four modules (e.g. an L1-4 serves 200 crystals in module 4). Module 1 has 500 crystals, so the symmetry is broken, with one L1-1 fan-out serving only 100 crystals. Each FEM (shaded) houses two reference PN photodiodes (pairs of fibers are shown hashed).*

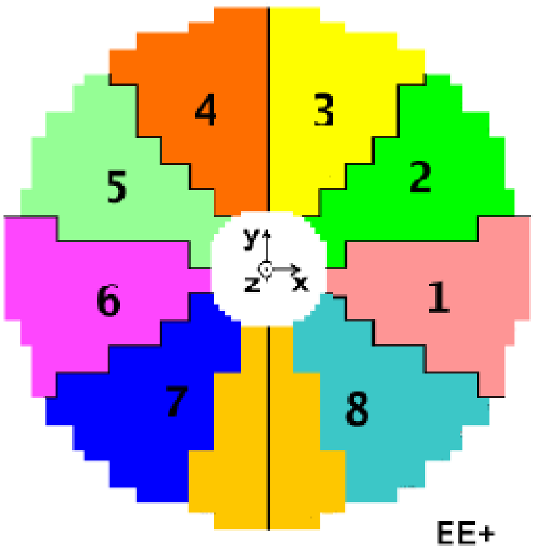


Figure 3: *Endcap laser monitoring regions. The regions are separated by black lines and numbered here from 1 to 8. The colours represent the DCC regions.*

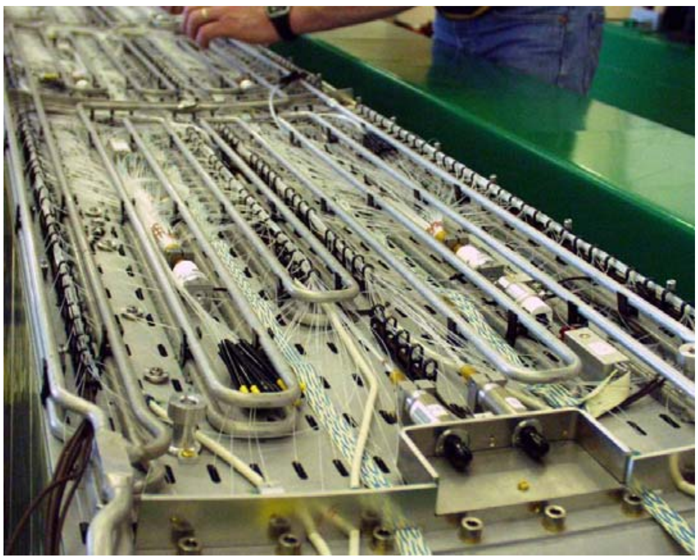


Figure 4: *module 4 of an ECAL Barrel supermodule (front cover removed) showing the monitoring light distribution components mounted on the front face (LHC beam-line would be overhead in this view). Laser light enters the SM via primary fibers connected to the two secondary distribution fan-outs (L2A & L2B) visible at lower edge (only one of these is pulsed at a time).The pulses are subsequently distributed to tertiary (L1) fan-outs along the SM on either side of the central axis; the two L1-4 fan-outs are visible here.*

4 Description of the light source system

4.1 Laser description

The CMS ECAL monitoring light source consists of three laser systems, each with their own diagnostics, two fiber optic switches, internal monitors and corresponding PC based controllers. Fig. 5 and 6 are the 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 its power supply and cooler unit and corresponding transformer, a Ti:Sapphire laser 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.

All 3 pump lasers are model 527DQ-S Q-switched Nd:YLF laser, which is a commercial product by Quantronix Inc. 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. 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.
A total of 4 wavelengths are available: **440nm** (blue to follow crystal's radiation damage), **495nm** (green, for redundancy), **709nm** (red) and **796nm** (infrared, cross-check of gain variation).
The laser light pulses are directed to individual crystals via a multi-level optical fiber distribution system:

1. a 1x5 optical switch elects one of the 3laser source;
2. a 1x100 optical switch directs the pulses to one of 88 calorimeter elements
3. a primary optical fiber distribution system transports the pulses 95 to 130 m to the each calorimeter element mounted in CMS located in the experimental cavern UXC5
4. finally, a two-level distribution system mounted on the detector sends the pulses to the individual crystals.

A monitoring 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 histograms and history of laser 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.

	YLF*	Ti:S 1		Ti:S 2	
λ (nm)	527	440	495	796	709
Pulse energy (mJ)	20	1	0.5	1.5	0.42
Pulse width (ns)	100-170	25-30	40-50	25-30	30

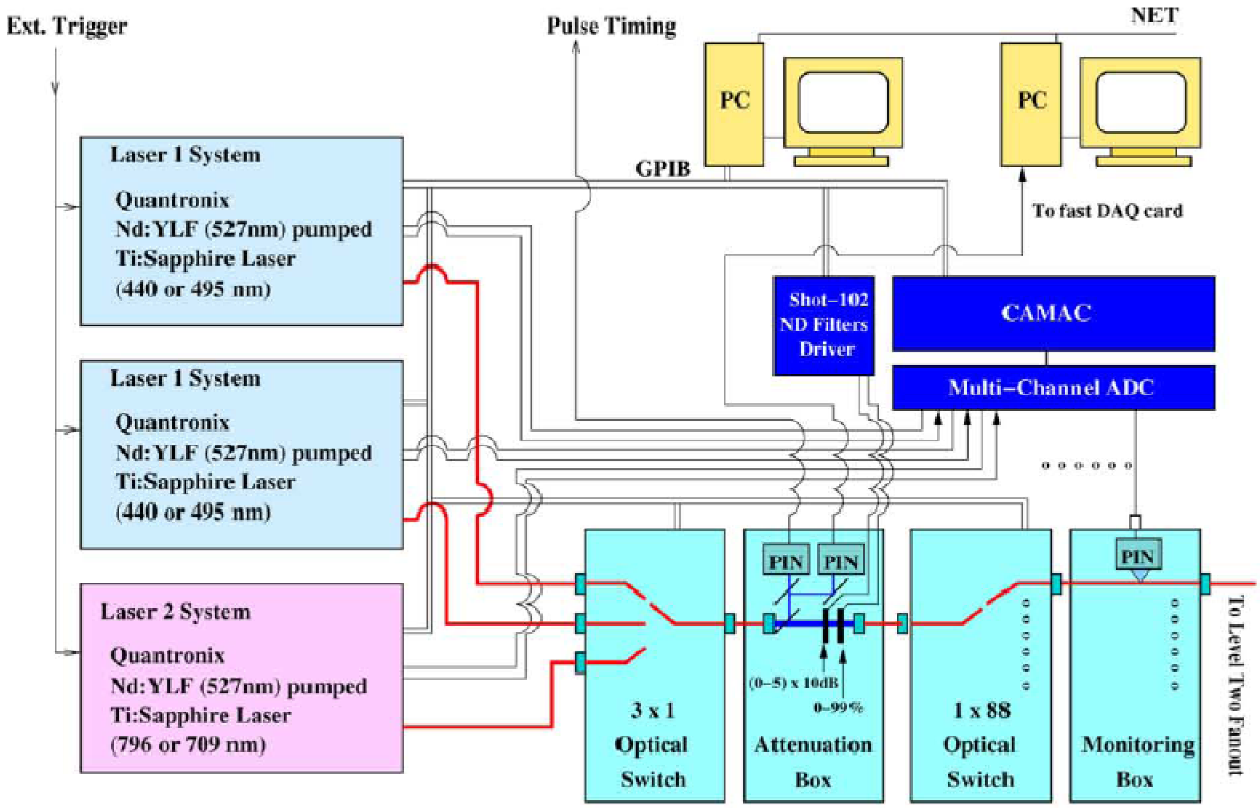


Figure 5: *A schematic showing the design of the high distribution system.*

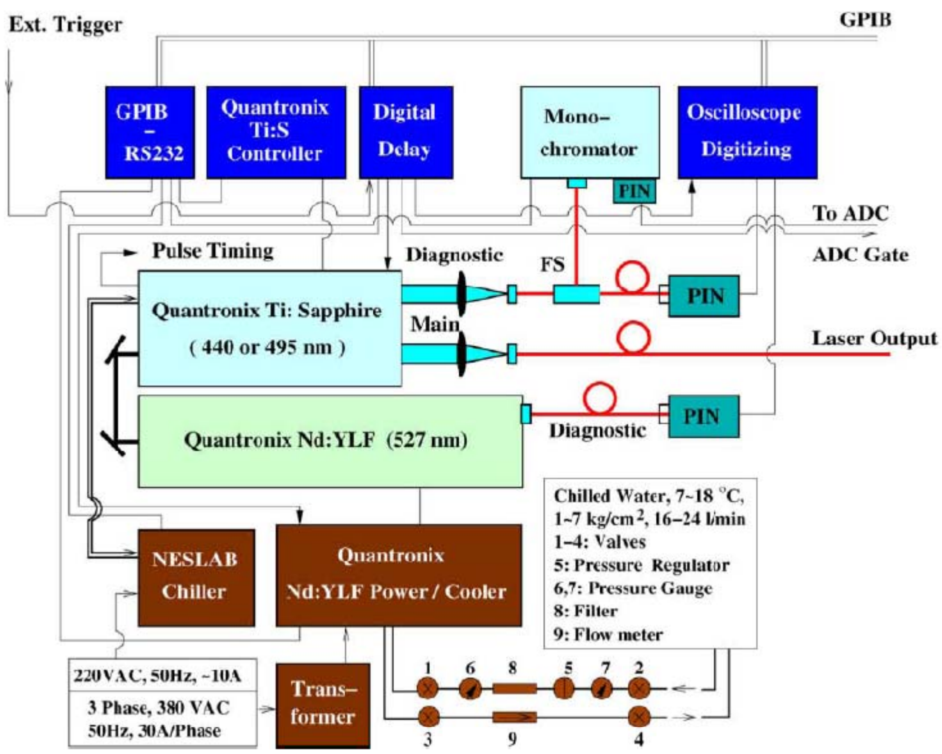


Figure 6: *A schematic showing the design of the laser based monitoring light source.*

As shown in Figure 7, each laser are enclosed to a softwall clean room in order to have:

- . cleanroom class <10,000 (measured < 1000)
- . temperature stabilized to ± 0.5 °C
- . Humidity <60%

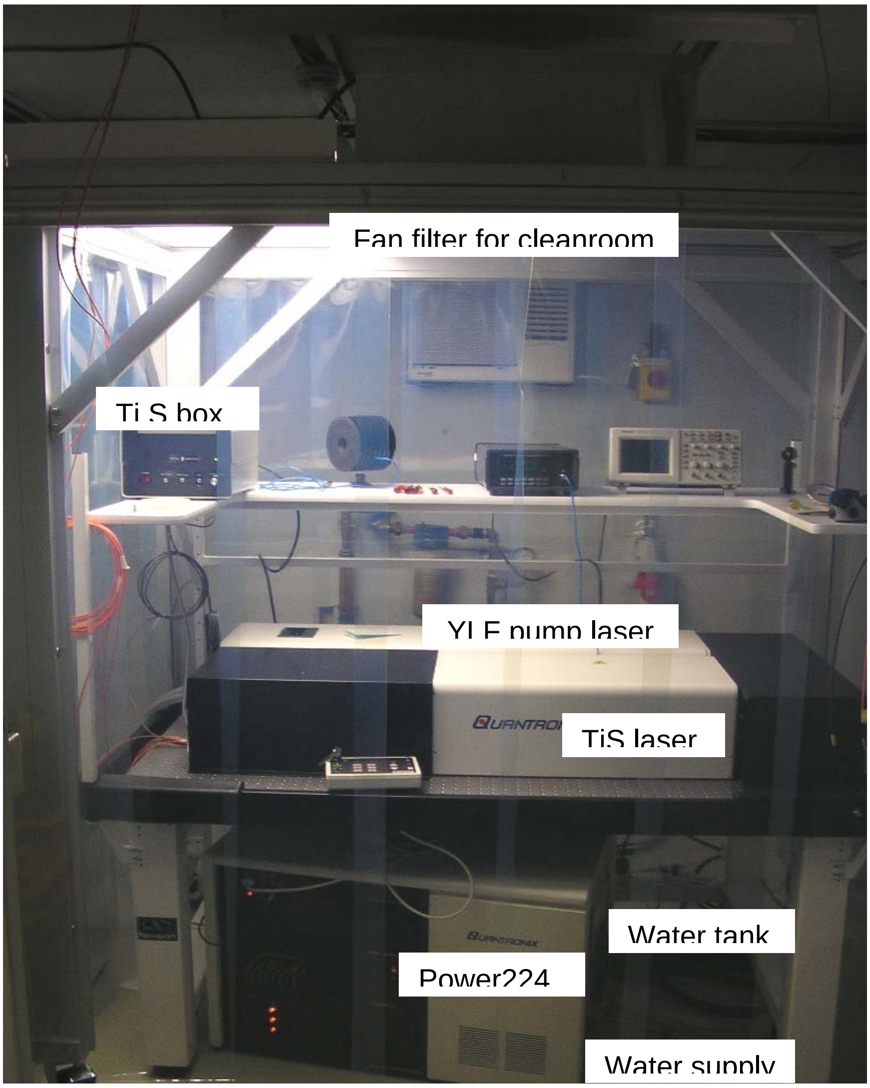


Figure 7: *Picture of one laser room.*

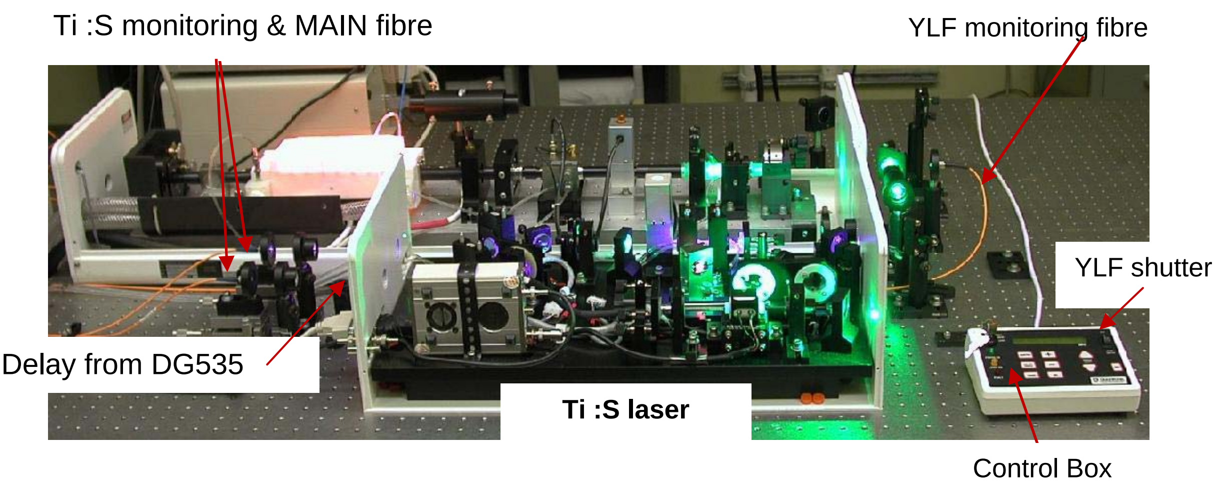


Figure 8: *Picture of laser itself.*

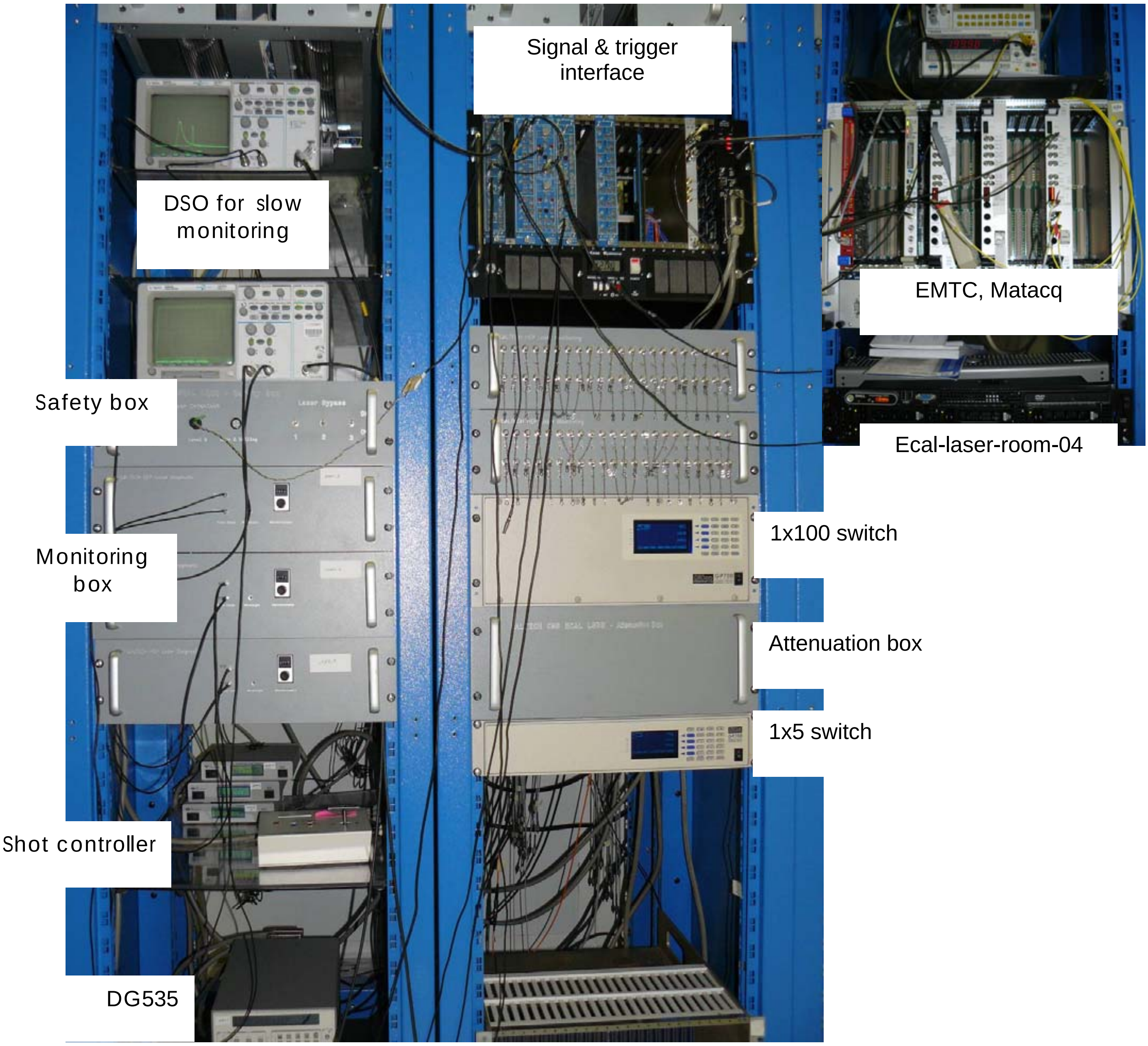


Figure 9: *Rack description*

List of Devices:

PC ecal-laser-room-01.cms: fast monitoring, Acqiris DP210.
PC ecal-laser-room-02.cms: slow monitoring, GPIB interface.
PC ecal-laser-room-04.cms: rack PC ecal supervisor (EMTC)

Safety Box: Input: All the doors interlock – flash lamps – Level2 (5V) – operating mode (maintenance or normal)
Output: YLF shutter and power supply interlock.

ICS device, Serial RS232 to GPIB interface (laser 1, 2, 3):
Input: TiS, Power224, Neslab RS232
Output: GPIB

DG535 digital delay (laser 1, 2, 3):
Ext trigger: Come from EMTC through a fan in/out unit for distribution.
NIM (threshold -4V)
T0: Connected to DSO trigger.
A: Connected to YLF external trigger input.
B: Connected to Ti:S laser (input delay of HV pulser on laser)
C: Not in used.
D: Connected to Acqiris trigger through coincidence unit.

SHOT102 controller:
Stepper controller for linear and logarithmic attenuation.

Monitoring box (laser 1, 2, 3):
Input: monitoring fibre YLF and TiS;
Output: signal from pin diode for slow monitoring (DSO);

Optical Switch 1x5
Input: Main TiS fibre from the 3 lasers
Output: 1 fibre to the attenuation box

Attenuation box
- Neutral density filters : 0, -10, -20, -30, -40, -50 dB;
- Linear attenuation: 0 to 100% *(0.4dB to 27dB loss)*;
- Pin diode for Acqiris DP210 and Matacq (VME splitter)

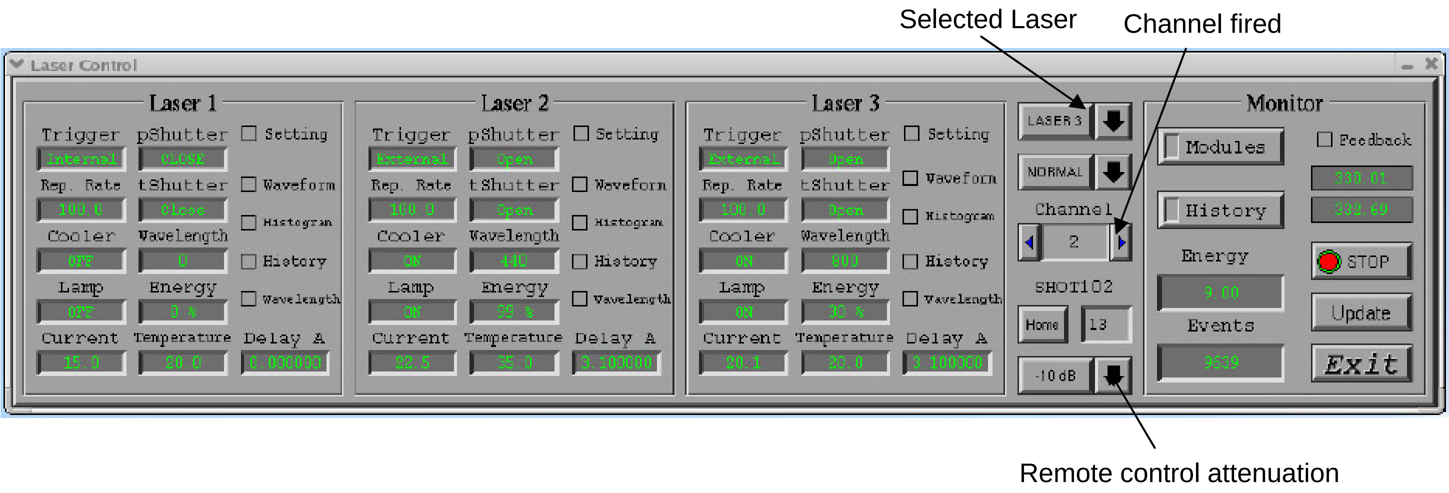
Optical Switch 1x100
Input: fibre from the attenuation box
Output: main fibres to ECAL

EMTC board (*Ecal Monitoring Trigger Card***)**
Input: 4 TTCci's input fibres. EE +- and EB+-
Output: 2 NIM signals for laser and Matacq trigger

Matacq
Input: pulse from attenuation box – triggering by EMTC
Data on *http://ecal-laser-room-03.cms/laser-fastcheck*

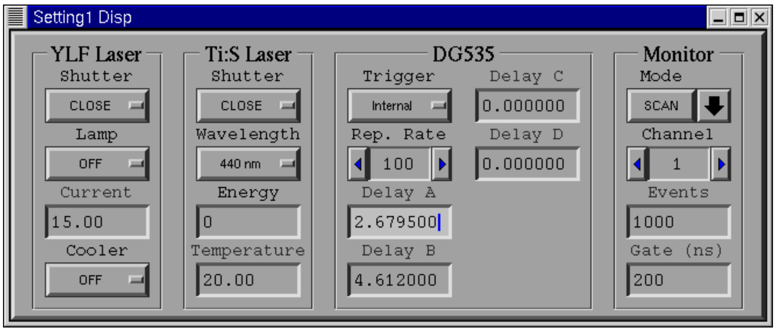
4.2 Slow monitoring

Running on **ecal-laser-room-02.cms** → #switch_test > **./laser2 || logfile.txt**

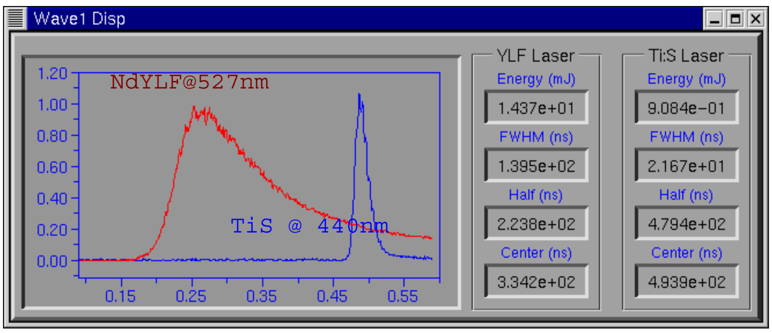


Main panel:
. display status of each laser: trigger, rate, cooler, lamp, current, shutter, wavelength, TIS energy and Delay A;
. attenuation : linear and logarithmic;
. laser online (1, 2 or 3);
. optical channel (1 to 88);
. Feedback buuton control;
. RUN/STOP acquisition button.

Setting:
check or adjust delays, laser shutters, trigger (internal or external), wavelength. Laser energy is 99% for blue and 40% for red laser.



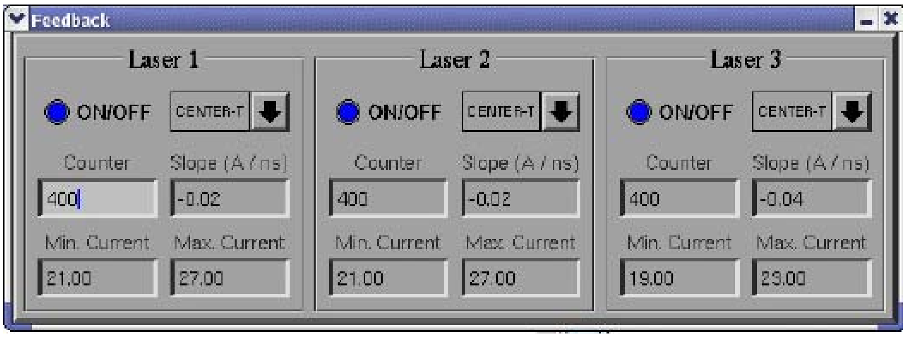
Waveform:
pulse information from DSO when DAQ is running → check TiS pulse informations.



UN/STOP button:
start and stop the monitoring acquisition.
On waveform display, be sure that pulses are display and parameters are OK.
Data are saved into .dat file and hbook file for the current month.

Feedback:

Feedback is used to increase laser current automatically to compensate aging of the lamp.



Current incremental step: 0.1A

Parameter: Energy – FWHM – Center
Counter: number of events required to calculate average values for the selected parameter.
slope: value define by calibration
current limit: min and max for laser protection.

Fig. 10 show correlations between the Nd:YLF laser pumping current and the laser pulse energy, FWHM and center timing for Nd:YLF laser and Ti:Sapphire laser respectively. Also shown in these figures are the numerical values of the slope defined at the Nd:YLF laser pumping current of 25 A. It is clear that the laser pulse energy increases and both the pulse FWHM and the pulse center timing decrease when the Nd:YLF laser pumping current increases. This is understood since the optical gain of the Nd:YLF crystal increases when the pumping current increases, and thus the built-up time of the laser pulse in cavity decreases and a shorter pulse width is generated. In principle, any parameter or a combination of these parameters can be used as the input to calculate feedback needed for trimming the Nd:YLF laser pumping current and thus compensating the DC Kr lamp aging effect. Looking into the slope values of these parameters in Fig. 10 and their sensitivities as compared to the corresponding r.m.s. values of the parameter, however, the Ti:Sapphire laser pulse center timing is preferred as the feedback input. A software feedback control was designed in the laser control and DAQ program. Fig. 11 is a schematic describing the basic operation of the software feedback. When the software feedback is enabled, the program first calculates an average of a selected parameter for a defined event number.
This average is then compared to a predefined number and their difference is used to calculate an incremental variation of the Nd:YLF laser pumping current by using the corresponding slope. If the absolute value of the incremental variation is larger than 0.1 A, then the Nd:YLF laser's pumping current is trimmed correspondingly, otherwise not. This amplitude of 0.1 A is limited by the Quantronix Nd:YLF laser control hardware. Upper and low limits of the Nd:YLF laser pumping current are also set for laser safety. The Nd:YLF laser pumping current will stay unchanged when it reaches the upper limit, indicating that the DC Kr lamp needs to be replaced.

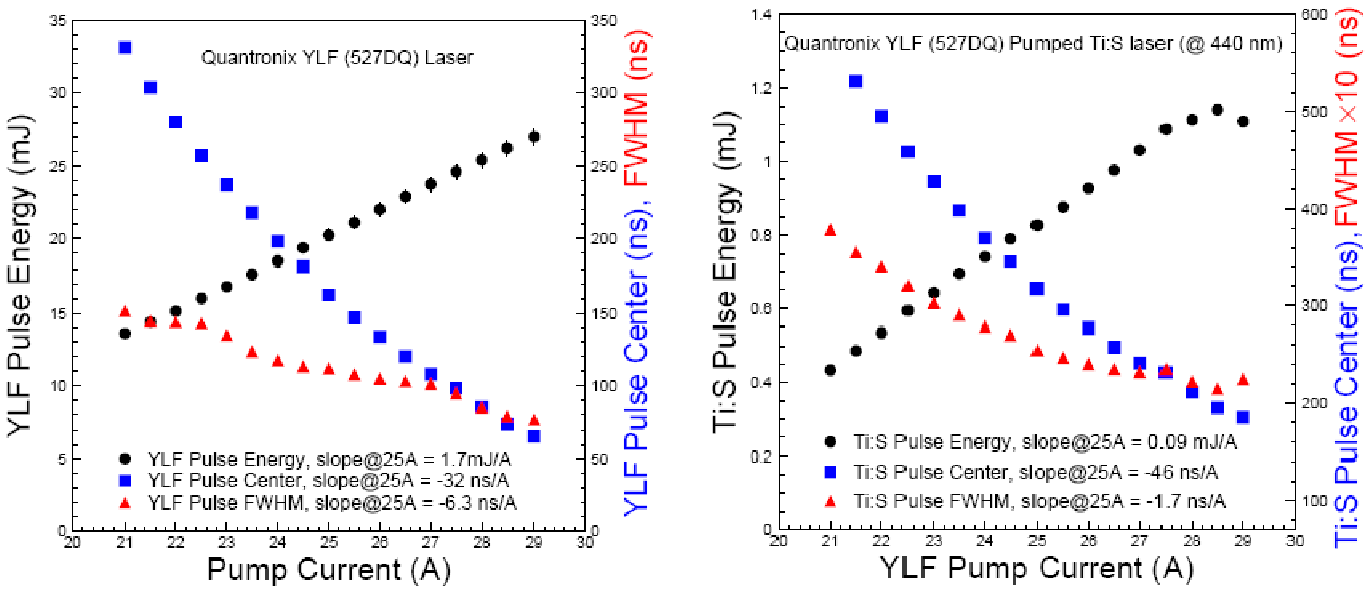


Figure 10: *Correlation between pump current and pulse energy: YLF (pump) and TiS (blue)*

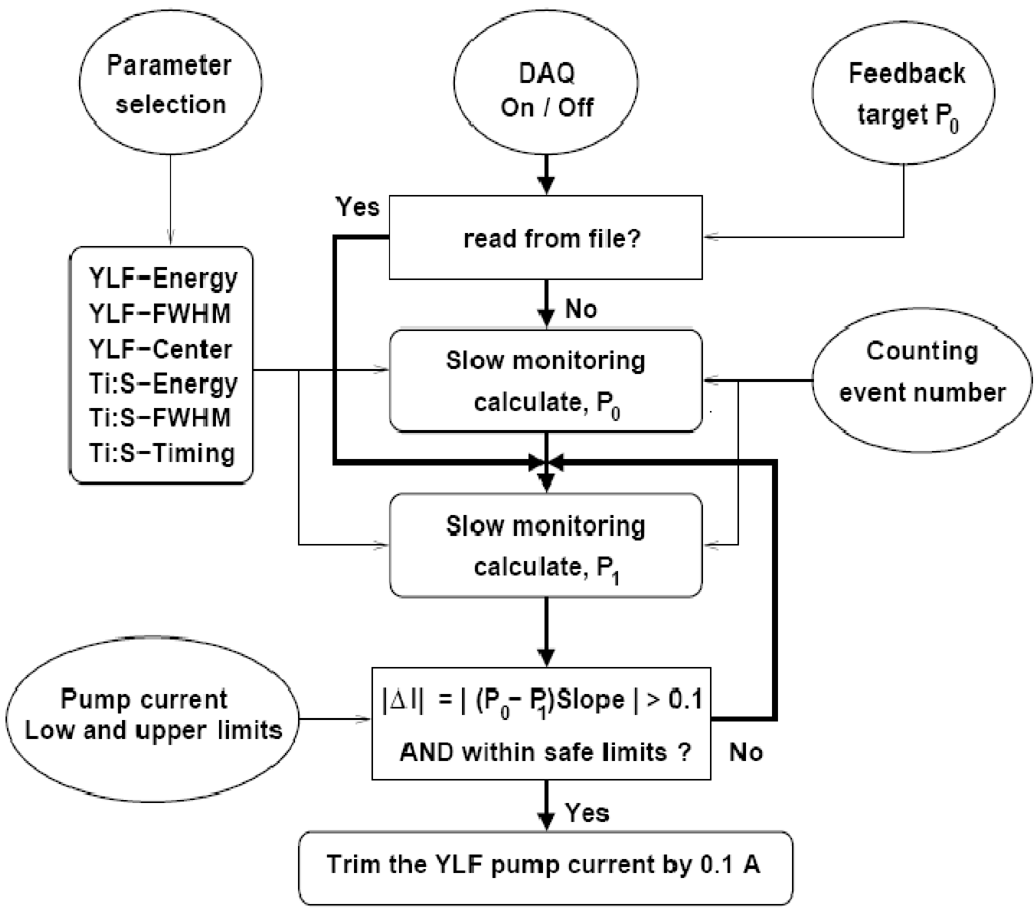


Figure 11: *Software feedback control*

4.3 Fast monitoring

Running on **ecal-laser-room-01.cms** → #monitor/src> **./monitor**

PCI board DP210 digitizer Acqiris 2: sampling each laser pulse at 2Gs/sec.

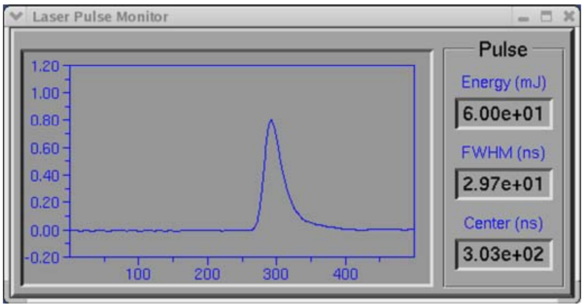


Figure 12: *display of 1 pulse event with Acqiris board*

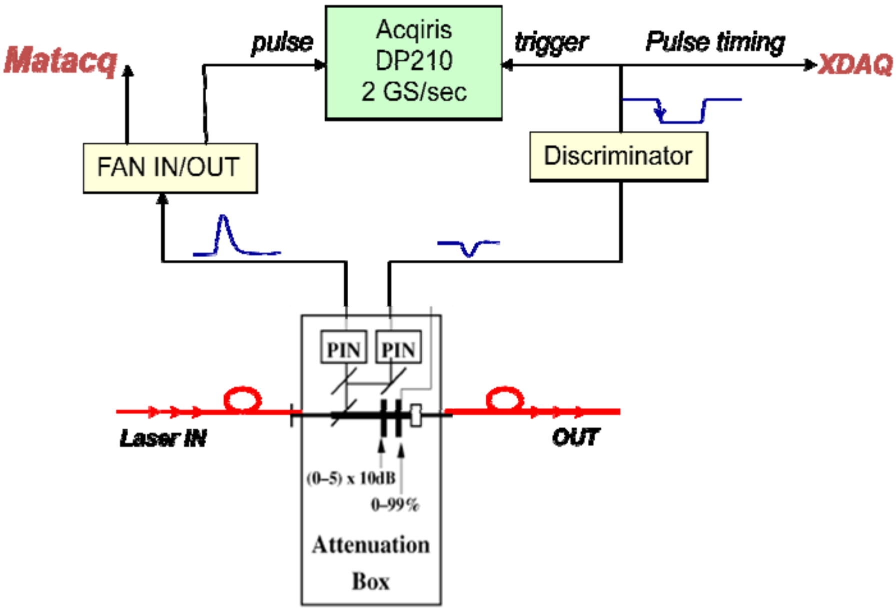


Figure 13: *schematic of the fast monitoring*

4.4 Attenuation box

The attenuation box is placed between the 2 optical switch.
The 2 attenuation wheels are controlled by the SHOT102 stepper controller.
Pin diodes are used to create fast monitoring pulse and trigger.

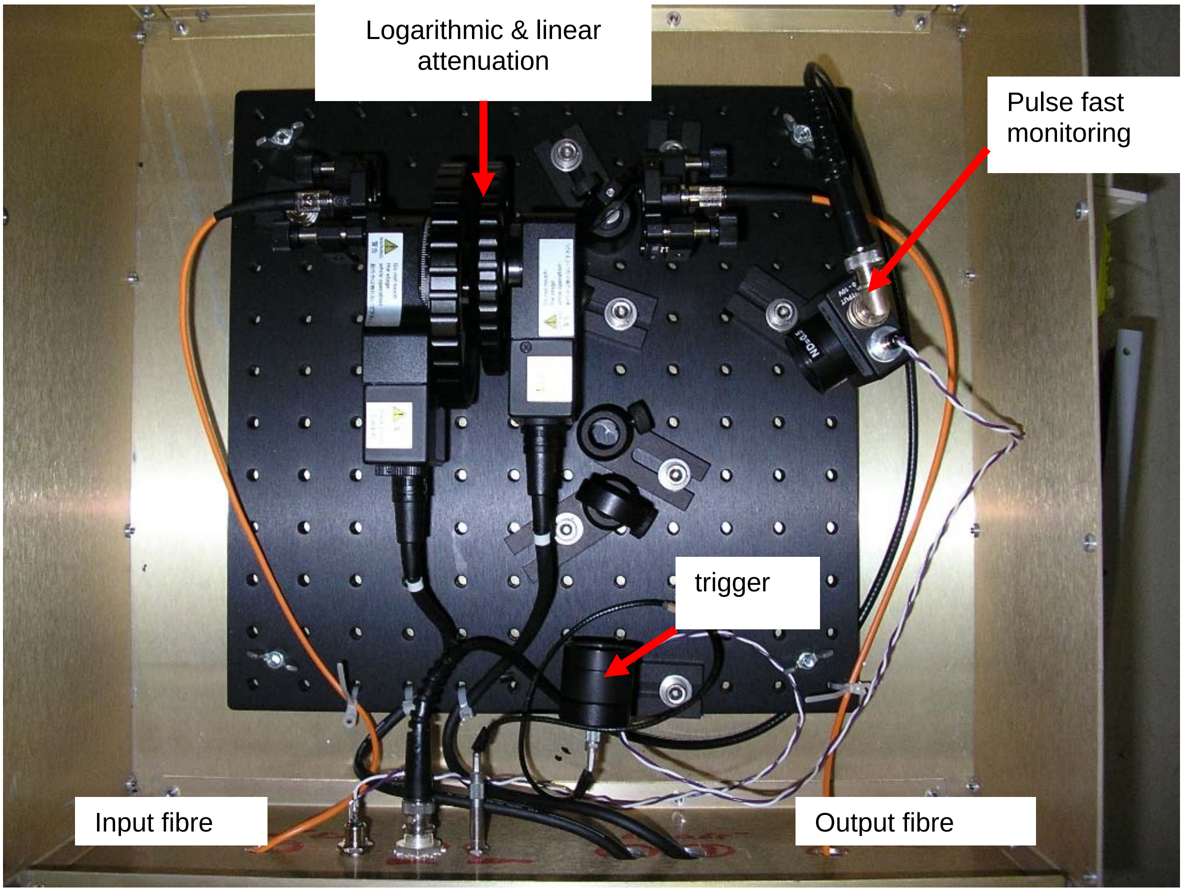


Figure 14: *attenuation box*

Neutral density filters:
0-10-20-30-40-50 dB

+

Variable Reflective Neutral Density Filters

Optical Density from 0.04 - 2.7

Remote control (XDAQ): 1% by 1%

0% = min. power (27 dB loss)
100% = max power (0.4 dB)

4.5 Laser safety

The users have to follow CERN regulations: access to the laser barrack restricted to the authorized person:

. Special access request through EDH;
. Need to follow a laser lesson at CERN (TIS/GS).

All the safety is controlled by the safety box:

- Outer door : interlock + flash lamp
- Inner doors : 3 interlocks
  3 boxes: Flash LED+ yellow LED

2 modes of operation:

The inner and outer door of laser barrack can't be opened at the same time else the YLF shutter is going to be closed.

1) **Normal operation** : inner doors should be closed and you can enter in the barrack: YLF shutter won't be closed
2) **Maintenance operation**: inner doors can stay opened to work on the laser: the outer door controls the shutters. If someone from outside enter to the barrack the shutter is closing.

5 Sequence of operations

5.1 Sequence description

A laser-monitoring sequence consists of a complete scan of the ECAL with 2 wavelengths (blue and red), pedestals measurement of the MGPAs and electronics stability check with Test-Pulse. The laser-monitoring sequence will not include a scan of the End-Caps with the red laser since the VPT used in the End-Caps are not sensitive to the red wavelength. In order to be able to measure and correct the changes in the crystal transmission in an efficient way, even at the beginning of beam periods, we need to perform a laser-monitoring sequence every 30 minutes.

The laser monitoring procedure should run such that one gets a full reference point for CMS-ECAL every 1/2 hour. Other complementary measurements will be performed during beam-off periods, as summarized in the next table:

Event type	LHC gap	beam off
laser	2 wavelengths G12	3 wavelengths free gain G12-G6-G1
pedestals	G12, G6$^{(*)}$	G12-G6-G1
PN test pulse	G16	G16-G1
APD test pulse	G12$^{(*)}$	G12-G6-G1

Such a sequence cycle time is given by:

$$t_{seq} = (88 + 72) \times (600 + 200 + 200)/f_{pulse} + 2\ t_p$$

We propose to take 200 pedestal and 200 test-pulse events (or 400 empty events) before taking laser data on a monitoring region to let time to the optical switch to set in the correct position. The time for changing optical switch channel has been measured to be 2s (with laser monitoring on). We take a safety factor of 2 and thus acquire 400 extra events in between 2 laser runs on 2 consecutive monitoring regions. We assume tp = 28 s, is enough to set the optical switch and the optical attenuator in position when we switch from one laser to another. The minimum time required for a laser-only calibration sequence with fpulse=100 Hz is:

$$T_{seq} \sim 28\ \text{mn}$$

The trigger sequence required for the described monitoring sequence can be summarized by the formula:

$$(200.Ped + 200.TP + 600.L_{blue}) \times 88 + 2800.e + (400.e + 600.L_{red}) \times 72 + 2800.e$$

where 'Lred' (resp. 'Lblue') represents a calibration trigger used to acquire a red laser (resp. blue laser) event, Ped is a pedestal trigger, TP is a test-pulse trigger and e represents an "empty event" trigger. The number of pedestal, test-pulse and empty events can be tuned to accommodate to the actual behavior of the optical switches and attenuators. For instance, if the time to switch from one monitoring unit to another one can be reliably set at 2 seconds, the total time needed to perform a laser monitoring sequence can be reduced to 22 minutes.

5.2 Sequence driving

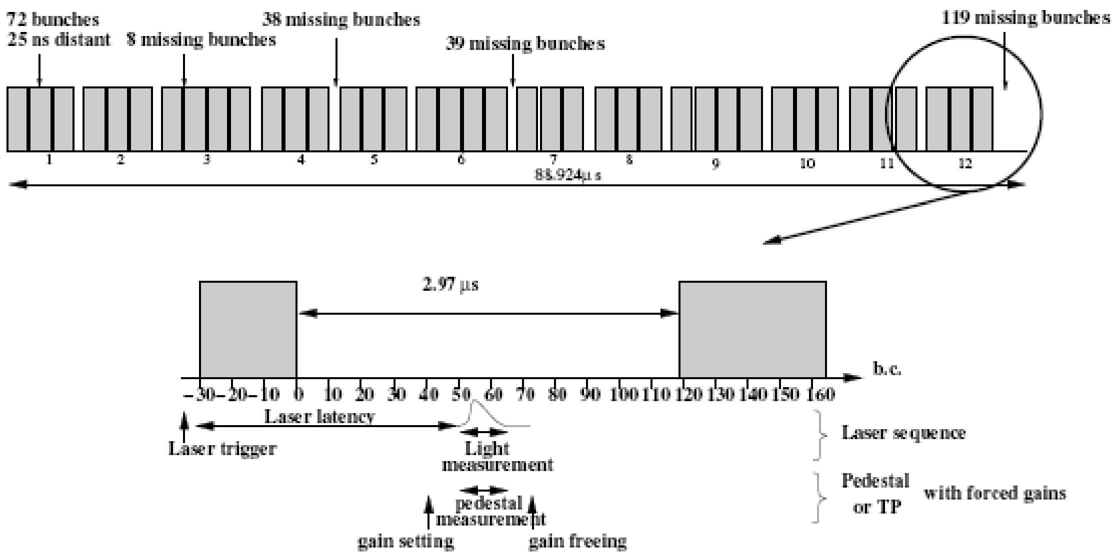


Figure 15: *Example of monitoring cycle within LHC cycle*

The **TCS** (trigger control system) will be responsible during normal LHC running conditions for driving the monitoring sequence. It decides which gap will be allocated to the gap-events in CMS. On reception of a calibration trigger (**Test Enable, TE),** a predefined sequence loaded in the TTC system will send to the ECAL all the information necessary to set the laser system (monitoring unit, wave length, actual power) and the Read-Out electronics. To handle with the delay needed by the laser to pump before sending a light pulse, a signal (**Warning Test-Enable, WTE**) is send by the TCS before each TE. The WTE will be received 400 clocks before the TE signal.

The trigger is distributed in the LHC experiments through the Trigger, Time and Command (TTC) system. The TTC is a communication system based on a 80MHz synchronous link composed of two time division multiplexed channels; one channel, channel A, is used to sends the commands requiring the minimum latency, in principle the level one trigger accept (L1A); the second channel, channel B, is used to send different fast commands.

The TTC is divided in partitions, including 4 for the ECAL: one for each endcap and one for each half-barrel.

The partitions can run in parallel and receive different triggers but in a normal physics run all the partitions receive the same triggers. The TCS sends the trigger (and other TTC commands) to the input cards of each partitions, called TTC-ci (TTC CMS input). The TTC-ci's are then responsible to distribute the trigger and TTC commands inside the trigger partition, in particular to the Front-End readout. The trigger distribution is made through 1310nm multimode optical links, a dedicated chip, the TTC-Rx is used to decode the TTC signal.

In order to receive the trigger of the 4 ECAL partitions, 4 optical receivers and 4 TTC-rx chips are required.

The TCS will send regularly, at a frequency of about 100Hz, **calibration trigger** which can be used by the subdetectors to acquire calibration data during **LHC main gaps**, Fig.15.
A B-channel command, ”Test Enabled” (TE) is sent in advance to the TTC-ci's indicating that the next L1A is for calibration. The TTC-ci's translates received TEs into the TE commands distributed to the connected TTC-Rx. The sent commands are specific to the calibration task of each sub-detector. For ignoring a TE, a ”*send an empty event at next L1A*” command is sent. The monitoring laser will be triggered by a ”***laser trigger***” send by the TTC-ci upon reception of a WTE signal. A programmable delay is available in the EMTC (see next section) to tune the actual delivery time of the light pulse to be in the LHC abort gap. With this system, the LV1 timing remain the same whatever the event type (laser,test-pulse, pedestal).

5.3 Laser trigger system: EMTC

The interface between the laser and the TTC will be done with a dedicated card, the ECAL Monitoring Trigger
Card (**EMTC**). The EMTC will receive the signals generated by the ECAL TTC-ci's upon reception of the WTE, the TE and the L1A through 4 TTC optical inputs, one for each ECAL partition. This card will provide two NIM triggering signals, one to trig the monitoring laser, one to trig the MATACQ acquisition stop. This is a 6U-VME board which will be located in the same crate as the MATACQ near the laser diagnostic system. The following information is sent together with the TE signal:

• The calibration trigger type : pedestal, test-pulse, laser, empty gap-event.
• The laser wavelength : Blue, green, red, far red, led1, led2.
• The identification of the ECAL monitoring region which is under study.

The identification of the ECAL region is used by the DCCs to limit the readout to the monitored region; the laser wavelength information is sent with the TE in order to be inserted into the laser event headers. The EMTC will decode the ECAL region information and inform the laser supervisor to switch to another position whenever it is required. This will be done during test-pulse and pedestal measurements inserted between 2 consecutive laser sequences of 600 events. The EMTC will wait for a ”ready” signal, until which it will inhibit the laser trigger. With this setting, the laser system will run in a complete slave mode. The online monitoring will check the consistency of the data and warn ECAL shift crew in case of desynchronisation of the sequence.

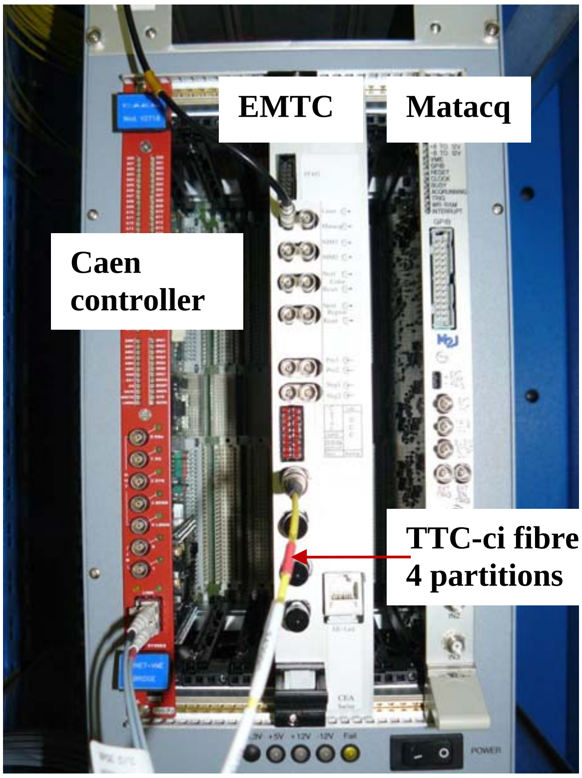


Figure 16: *laser supervisor controller, EMTC, Matacq*

The identification of the ECAL region is used by the DCCs to limit the readout to the monitored region; the laser wavelength information is sent with the TE in order to be inserted into the laser event headers. The EMTC will decode the ECAL region information and inform the laser supervisor to switch to another position whenever it is required. This will be done during test-pulse and pedestal measurements inserted between 2 consecutive laser sequences of 600 events. The EMTC will wait for a ”ready” signal, until which it will inhibit the laser trigger. With this setting, the laser system will run in a complete slave mode. The online monitoring will check the consistency of the data and warn ECAL shift crew in case of desynchronisation of the sequence. The laser-monitoring sequence can be achieved by setting the TTC-ci B-Go(2) postscale parameter to 200 and
filling the TTC-ci B-Go(2) FIFO with

$$(Ped + TP + 3L^{\mathrm{blue}}) \times 88 + 14.e + (2.e + 3L^{\mathrm{red}}) \times 72 + 14.e$$

This pattern is actually:

$$(Ped1 + TP1 + 3.L^{b}_{1}) + ... + (Ped_{88} + TP_{88} + 3.L^{b}_{88}) + 14.e + (2.e_{1} + 3.L^{r}_{1}) + ... + (2.e_{72} + 3.L^{r}_{72}) + 14.e \qquad (1)$$

where L^{blue}_{i} , L^{red}_{i} , Ped_i, TP_i and e_i represent the triggers sent to the monitoring region *i.* The trigger sequence (Eq.1) is 828 long. The FIFO is large enough to contain the whole sequence at once so the repetitive mode can be used. The FIFOs of the 4 TTC-ci’s must be filled with this sequence. In the FIFO of a TTC-ci the L_i trigger commands for the monitoring region covered by the three other TTC-ci’s may be replaced by ”empty event” commands.

The synchronized TTC-ci B-GO(13) FIFO to handle the WTE will be :

$$(2.NoOp + 3.trigger) \times 88 + 14.NoOp + (2.NoOp + 3.trigger) \times 72 + 14.NoOp$$

where *NoOp* means that the TTC-ci does nothing for this WTE and trigger means that the TTC-ci encodes the
”laser trigger” signal.

Ideally, the information to propagate on reception on a TE by the TTC-ci is the following:

- Monitoring region to consider: 6+1 bits (DCC number/side).
- Event type: 3 bits (pedestal/TP/Blue/Green/Red/IR/LED1/LED2/empty)
- Laser power: 7 bits (0-99 %)
- Laser attenuator: 2 bits (0-10-20-30 dB)

In normal monitoring sequences, the laser power and the laser attenuator have not to be changed and the information has not to be propagate through the TTC system.

Laser control PC: running on **ecal-laser-room-04.cms**

The EMTC control software and the laser control software will run in different processes. The communication between the processes will be done through a TCP/IP connection (XDAQ can be used as communication framework but it is not a requirement).

6 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, 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.

Fig. 17 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%. 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 180 nm, its intensity, and thus stability, at 709 and 495 nm off the peak emission is limited.

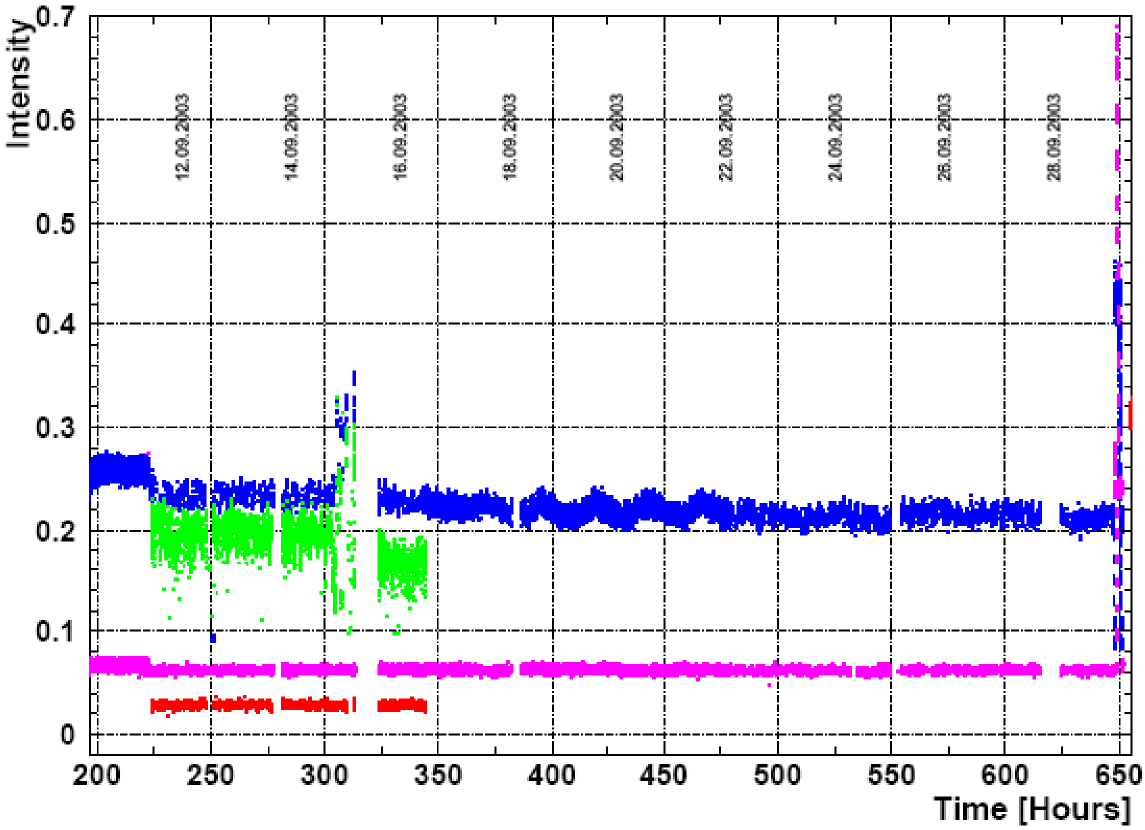


Figure 17: *Laser pulse intensity is shown as function of time (h) during a 19 day period in a beam test at CERN, where blue, green, pink and red represent laser pulse energies at 440, 495, 709 and 796 nm respectively. Vertical spreads in the middle left (320 h) and right (650 h) are laser pulse energy scan runs for electronics test.*

Laser stability with software feedback

The software feedback control was first implemented for individual laser runs during ECAL tests in 2006 at CERN. Fig. 18 and Fig. 19 summarize typical laser performance at 440 nm for two laser runs without and with the software feedback control lasting for 130 and 180 hours respectively. The effectiveness of the software feedback is clearly observed. As shown in the histograms at right, significant improvement was observed in stabilities of the laser pulse energy (2.3% to 1.4%), pulse FWHM (3.1% to 2.0%) and pulse center timing jitter (4.1 ns to 1.8 ns) by using the Ti:Sapphire pulse center timing as the feedback parameter. By defining the laser pulse timing, the software feedback control was made to work across laser runs. Fig. 20 shows history and histogram for combined Ti:Sapphire laser runs at 440 nm with a total run time of more than 2,000 hours. At left is the history plots of the laser pulse energy, FWHM, pulse center timing and the YLF pumping current. Each data point represents one hour average of the slow monitor data. The effectiveness of the software feedback control is clearly shown in the laser pulse timing history, where degradations are compensated by the YLF pumping current adjustment at 0.1 A a step from 22 A to 23.8 A. The overall stability of the Ti:Sapphire laser pulse energy and FWHM is 3.0% and 3.4% respectively, much better than the 10% specification. The corresponding pulse jitter during this period is 1.9 ns, much better than the 3 ns specification. We also notice four jumps in the FWHM history occurred at 220, 420, 750 and 1,700 hour. These jumps are suspected to be caused by temperature variations in the laser barracks at CERN test beam site. Although the Ti:Sapphire laser's SHG crystal is thermally stabilized by a Neslab chiller, variations of the room temperature would slightly change the Ti:S SHG crystal's matching angle, thus compromise the SHG crystal's conversion efficiency. These jumps may also related to the water filling operation for the Neslab cooler, which changes the stabilized temperature by 0.5^{o}C. Environmental temperature dependences of the Ti:Sapphire laser pulse performance were measured. The slope was found to be -4.3%/^{o}C, 1.3 ns/^{o}C and 7.9 ns/^{o}C respectively for the laser pulse energy, FWHM and pulse timing. The poor temperature stability observed in the laser barracks at CERN test beam site will be improved *in situ* at LHC, where the laser barracks are central air-conditioned with a temperature stability of better than 0.5^{o}C.

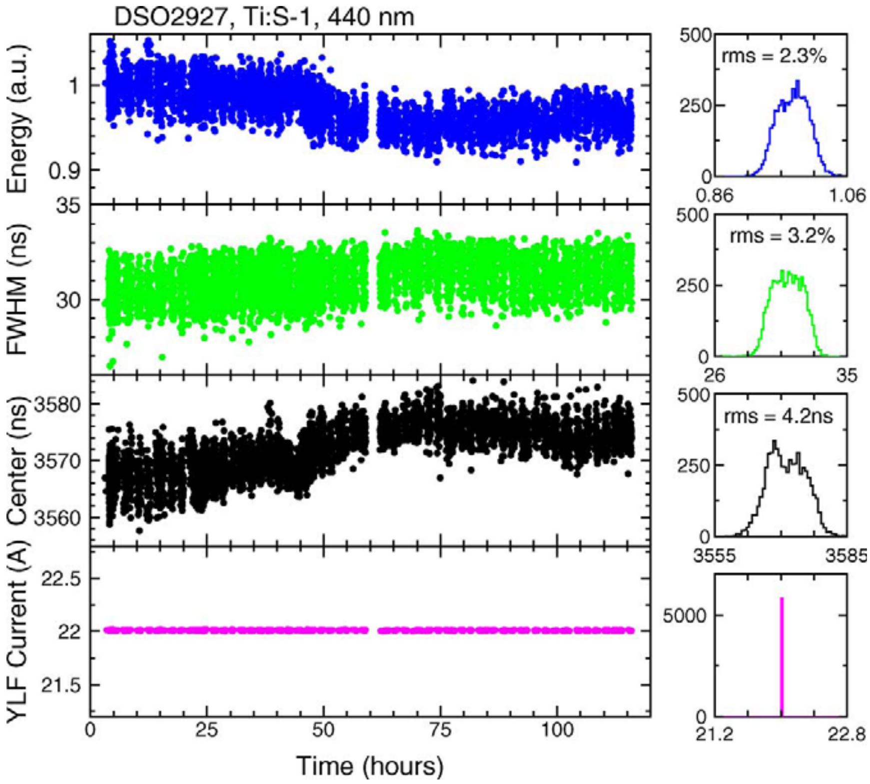


Figure 18: *Histories of the laser pulse energy, FWHM, pulse center timing and corresponding YLF laser pumping current are shown as function of time for a Ti:Sapphire laser run at 440 nm without feedback for more than 130 hours. The corresponding histogram distributions are shown at right.*

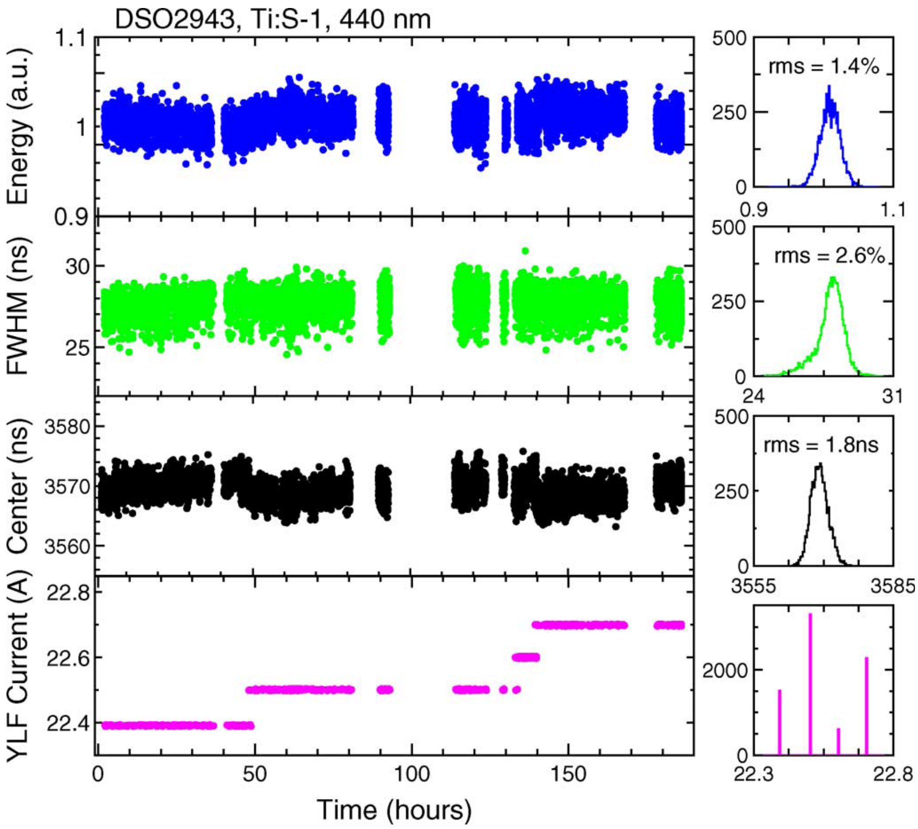


Figure 19: *The same as Fig. 6 for a Ti:Sapphire laser run at 440 nm for more than 180 hours by using the Ti:Sapphire laser pulse timing as the software feedback parameter.*

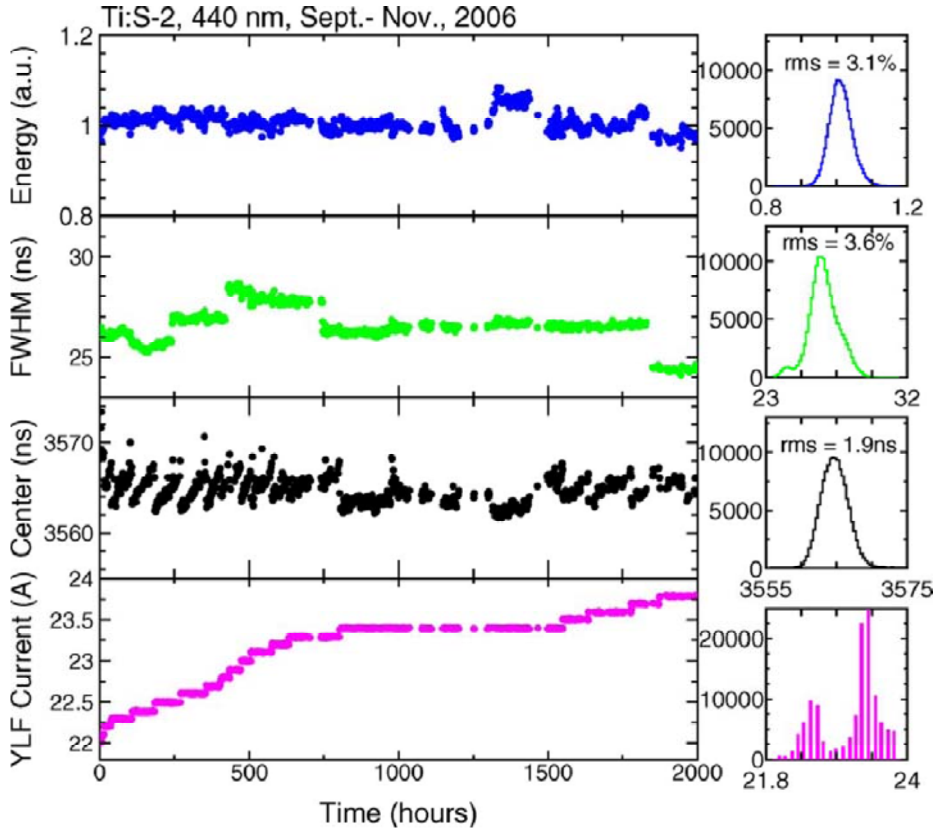


Figure 20: *The same as Fig.19 for combined several Ti:Sapphire laser runs at 440 nm for more than 2,000 hours.*

7 Summary

A multiple wavelength laser monitoring system for the CMS ECAL has been designed and constructed: the monitoring light source, diagnostics, and high level distribution system at Caltech and the calorimeter light distribution system, reference PN photodiode system, and associated electronics at CEA-Saclay.

Commissioned and validated at the CERN test beam facility, the measured performance of 0.068% stability in optical transmission measurements at the principle wavelength (440nm) over 11.5 days demonstrates the system's capability to achieve ≤ 0.15% drift/month stability required for precision crystal calorimetry at the LHC.