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The E781 Calorimeter Light Monitor System

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Abstract

The E781 photon calorimeters can be used reliably only with the aid of a dedicated light pulse monitor system. Our Light Pulse System (LPS) consists of LEDs and a high-powered N_2 laser and dye laser. They deliver short 20/60 ns (LEDs) and 4 ns (laser) light pulses to the calorimeter elements via optical fibers. The laser and LED outputs, which have stabilities of 3% or worse, are monitored at various stages of the light distribution system by highly stable PIN photodiodes on a pulse-by-pulse basis, and by a photomultiplier that also views a highly stable light pulse standard based on an ^{241}Am alpha source. The laser and LED light pulse intensity is known precisely via an off-line normalization to the reference photodiode and to the alpha source signals. The resulting stable light can then monitor the gain of 1680 lead glass channels of the E871 four photon calorimeters over many months of running with $< 1\%$ accuracy.

In this report we describe the construction of the light distribution system and its main tasks. We discuss briefly the calorimeter construction, performance, calibration, monitoring, and photoelectron statistics calculations. Some component and stability tests carried out at ITEP and Tel Aviv are also included. Finally we propose the future work schedule and institution responsibilities.

1 Scientific background and objectives

The electromagnetic calorimeters employed in modern high energy physics experiments can be used reliably only with the aid of dedicated light pulse monitor systems. The calorimeters measure the energy and coordinates of relativistic charged particles or gamma rays by integrating the light emitted by the electromagnetic shower in a array of crystals, each readout by photomultiplier tube (PMT). Such calorimeters consist of thousands of readout channels operated over running periods of many months in variable beam environement, in which PMT gain drift as well as radiation damage of the crystal and component aging may change their calibration. Therefore, the calibration of each channel must be monitored and readjusted. Such information becomes crucial in the off-line analysis later. A very convenient method is to measure its response to a constant light pulse, simulating the physical signal of the shower.

Some calorimeter light pulse systems used Xenon or hydrogen flash tubes [1] or LEDs [2]. These systems have however limited timing, intensity, wavelength and stability characteristics. Intensity stability was generally monitored using light pulse standards based on radioactive sources or cosmic ray muons. Presently, laser light pulse systems have been adopted in many experiments due to their excellent characteristics: large pulse intensity, very short pulses, variable and nearly monochromatic wavelength band [3]. A single high power N_2 laser may distribute, via optical fibers, a light equivalent of hundreds of GeV to as many as 10,000 calorimeter channels [4].

In this report, we discuss the light pulse system for monitoring the electromagnetic calorimeters of the Fermilab SELEX/E781 experiment [5]. The system is presently under construction at ITEP Moscow, IHEP Protvino, Tel Aviv University, and FNAL. The stability is achieved via a ^{241}Am light pulse standard; and independently, with highly stable photodiodes placed at important points in the light distribution system. The monitor system should achieve better than 1% stability off-line via a software normalization to the photodiode signals.

The following important properties of the detector readout are monitored:

1. the number of photoelectrons/GeV/PMT for calibration and stability needs,
2. linearity of the PMTs and associated electronics readout chain,
3. time delays from the PMTs and from the pipeline electronics.

Other effects which will be studied are: radiation damage, aging and the effect of varying beam intensity and magnetic fields on the PMTs.

In section 2, we discuss the main tasks and the construction of the E871 calorimeters together with the associated light monitor system. In section 3, we discuss the construction of the laser system, and in sections 4 and 5 we present initial test results. The main future objectives, work schedule, and institution responsibilities are summarized in section 6.

2 The E781 light monitor system

The system consists of two independent light sources. These are (i) LEDs and (ii) a high power N_2 and dye laser. Both sources deliver short pulses via optical fibers to four electromagnetic calorimeters. The calorimeters are positioned at large distances and have very different dynamic ranges (see table 1). The light pulses are injected onto the front end of 1680 readout channels, each a lead-glass block readout by a PMT.

♣ *We need to check tabel 1 for accuracy and to complete it with the missing data by further TAU-ITEP-IHEP contacts in order to reach a full picture of the E781 calorimeter system.*

At E781, the calorimeters will be used in the energy range $1 - 600$ GeV. The present LED light intensity can cover only the $1 - 30$ GeV range. The large light-equivalent dynamic range, the light losses together with the large number of readout channels impose a very powerful light source, practically only a laser. (see section 3 for further discussion)

♣ *We need to find more powerful LEDs and ensure that the laser power covers the whole range assigned to each readout channel of the four calorimeters.*

The main elements of the system are:

1. a high-power N_2 laser coupled to a dye laser module,
2. a system of green and red LED light pulse sources,
3. a system of highly stable PIN photodiodes integrated at various stages of the light distribution system and monitoring it on a pulse-to-pulse basis,
4. a remotely controlled wheel containing several neutral density filters to attenuate the laser beam,
5. a first light distribution stage located near the laser which splits the beam into fibers running out to the four calorimeters,
6. several secondary light distribution stages located on each calorimeter which further split the light into the lead-glass blocks,
7. a data acquisition system for collecting and transfering data for detector systems with thousands of readout channels.

The E781 monitoring and calibration system will use FASTBUS, with a Fastbus Smart Crate Controller (FSCC) and the DART data acuisition system, linked to the experimental database.

2.1 Monitoring tasks

The main role of the monitoring system is to track the calibration constants of each lead-glass block during long periods between calibrations. The system must respond to the following tasks:

1. Monitoring the readout of all calorimeter channels by sending light pulses for a short time *during* and *between* beam bursts.
2. Reasonable schedule (i.e. spill intervals, light pulse rate and statistics) such as to minimize the amount of data taking required to achieve significant results.
3. Linearization for each readout channel. The linear response must be checked over the full dynamic range. For channels with non-linear response, appropiate corrections must be determined [6].

The need for in-spill monitoring is supported by the experience of similar calorimeter systems. For example, Powell et al. [7] found an average enhancement of 3% (increasing with the spill time) of the shower calibration signal at a beam rate of $\sim 10^5$ particles per spill. In the same conditions, the laser signal also showed a $3-4\%$ increase.

♣ *We need to decide on the need to monitor in-burst, to allocate a convenient time slot, and to decide on the exact monitoring schedule.*

2.2 Light distribution system

The layout of the E781 light distribution system is shown schematically in Fig. 1, reproduced from [11]. Its aim is to produce, control and distribute light pulses to each lead-glass block of the four calorimeters, as well as to determine its response.

In Fig. 2 we present a detail of the system for Photon I/II showing the pulsing mechanism. Upon receiving a trigger from the DAQ, the control module activates sequentially the LED light sources in the 6 light boxes and the laser. The light pulses are transmitted via optical fibers to all lead-glass blocks. The resulting PMT pulses are transfered to ADCs, and then the digitized data is stored. One optical fiber is linked to the reference module for monitoring needs. This process is repeated for each beam cycle, during and between the spills.

2.2.1 Light distribution box

In Fig. 3 (a) we show the sheme of the light distribution box of Photon I/II and in (b) the one for Photon III/III′. Photon I and II have 6 distribution boxes each while Photon III and III′ have one distribution box each.

The box is located close to the calorimeters and serves to collect light from LEDs located inside and from the laser via an optical fiber, and to distribute it uniformly to a bundle of optical fibers running to each lead-lass block of the calorimeter.

In the case of Photon I/II the fiber bundle is 3 cm in diameter and consists of 128 fibers. (Each fiber is actually a bundle made of hundreds of ~ 50 μm glass micro-fibers.) The length of each fiber in the bundle is 1.4 m and has a diameter of 3 mm. The fibers are attached to the front end of the lead-glass blocks via holes in the front panel of the calorimeter. The box is light tight and consists essentially in three elements:

1. light source (LEDs and laser)
2. light collector, coupling uniformly the source to the fiber bundle,
3. fiber bundle

There is one *red* LED (type 521-9500-003) and *three* green LEDs (type 521-9500-002). The box volume is thermostatically controlled, with temperature stable at $30 \pm 0.2°$C to ensure LED constant light output. Every box has its own electronic system of shaping amplifiers (or pulse formers marked as *pf* in Fig. 2) with avalanche transistors which activate the LEDs. The light pulses have the following characteristics:

– The laser pulse is 4 ns narrow with a PMT pulse width of ≈ 25 nsec and intensity which should reach 600 GeV.

– The green LED light pulse intensity per channel is equivalent to roughly 10 GeV, with a PMT pulse width of 120 nsec.

– The red LED light pulse intensity per channel is equivalent to roughly 30 GeV, with a PMT pulse width of 70 nsec.

See section 3.3.2 for further details and section 5 for preliminary test results.

2.2.2 Control module

After receiving an enable signal from the DAQ computer (see Fig. 2) a 1 kHz pulse generator begins sending pulses to the control module (CM). In this discussion, we assume that there is one CM for each of Photon I and II, and a third for Photon III/III′. The generator signals enter the CM, and are directed to different light boxes according to an input code.

♣ *We need to clarify the exact function of the light pulse control module and decide on the most convenient way to integrate the laser in this system.*

For now, we describe an example of a simple code that is a series of seven pulses (whose widths must be specified) coming from the computer to the CM of Photon I. During the first of these seven pulses, the pulse train is directed to box nr. 1, and sequentially to the boxes 2-6. The seventh code pulse directs the CM to output a pulse to trigger the laser. The CM sequentially fires green and red LEDs and the laser. Specifically, it triggers the operation of the avalanche transistor circuits that provide the pulses to the LEDs.

Triggering externally the laser is most desirable, however it was found during tests that it requires a ~ 1 hour stabilization period. A better solution is to keep the laser operational and use a shutter to cut the pulse train.

2.2.3 Reference module

The reference module (RM) consists of a PMT receving light pulses from:

– the light distribution system (LDS),

– the light pulser source (LPS).

Its function is to compare these signals, thereby measuring precisely any variation of the LDS relative to the LPS.

One optical fiber is used to send light to the RM. In the present CM this is easily done for the LED signals. For the laser signals the CM may be used as long as the light from all 6 bundles enter within the photomultipler gate. Here we do not assume that they are all timed (via adjusting fiber lengths) to arrive at this photomultipler simultaneously.

The RM for Photon I/II is sketched in Fig. 4. The laser and LED signals enter the module via an optical fiber while the LPS is glued to the PMT head by silicon grease. The light amplitude is detected by a FEU-85 photomultiplier and then fed to a shape amplifier. The RM is located below the calorimeter where the temperature gradient is minimal [8].

The RM for Photon III/III′ contains a LPS made of an Am^{241} alpha source diffused in a sealed NaI crystal, a FEU-84-3 photomultiplier and an input for red light from a Ц3000 LED.

The ratio between the mean LED and LPS signals is a measure of the global stability of the light distribution system. Preliminary measurements show that such monitoring by LEDs only gives a stability of $\leq 1.5\%$. Preliminary tests of the laser-photodiode monitor system, with temperature stable PIN photodiodes, gives a stability well below 1% (see section 4).

2.2.4 Light pulse standard

The LPS mentioned above has the following construction. It consists of a ^{241}Am alpha micro-source irradiating a thin $YAlO_3$:Ce scintillator crystal [8]. Due to the long $\tau_{1/2} = 432$ years half-life of the isotope, the diamond-like characteristics of the crystal and the solid mechanical construction (see Fig. 5), the pulser is highly stable and practically unaffected by the environment. The LPS is nearly point-like (diameter 5.2 mm, height 1.2 mm and ^{241}Am deposit below 1 mm) and is guaranteed between $10-40^0$C. However, since it has a temperature instability of 0.3% per ^{0}C, its temperature is kept constant by a surrounding plastic form screen. The scintillation light pulses have a rate of $40-80$ Hz, a decay time of 28 ns, and cover the wavelength band 320-420 nm. Further details about this pulser type may be found in [9].

2.3 Calibration procedure

2.3.1 Precalibration

As pointed out before [10], an absolute calibration of the E781 calorimeters via the light pulsing system is not possible. However the system may be used for precise *precalibration* without the need of an electron beam. By this procedure the high voltage of the PMTs may be adjusted in order to pre-equalize the gains. Similar systems [7] achieved gain pre-equalization within 20%.

2.3.2 Linear response

The shower energy is measured as

$$E = \sum_i \alpha_i A_i \tag{1}$$

where the summation extends on all modules containing the shower, α_i are the calibration constants (relating ADC counts to energy in GeV) and A_i are the measured amplitudes. This procedure, evidently assumes a linear response of all calorimeter elements. Therefore, an important task is to check the linear response of each readout channel. For particular channels with non-linear response appropiate corrections may be found in terms of a polynomial fit [6].

The linearization of the PMTs is accomplished by varying the percent light intensity by a set of neutral density filters, automatically moved into the light path using a computer controlled stepping motor, followed by recording the response of all PMTs.

We envision ~ 10 steps in the range $1-100\%$ transmission and $\sim 10^3$ pulses for each position which, for a 3% pulse amplitude dispersion, reduces the centroid error to $\sim 0.1\%$. In the present setup only laser light is availabile for this task since the filters are located in the primary light distribution system. The use of LED light as a primary source, thereby allowing to perform linearity checks, would be interesting but would require very powerful (combination of) LEDs.

♣ *We need to analyse the need to have an additional DC light source for PMT gain measurements.*

2.3.3 Calibration constants

The precision calibration of the lead-glass blocks will be carried out using a monoenergetic electron beam scanning the front end of blocks. The operational details of this procedure are discussed in detail in [11]. It will require 5, 20 and possibly $50 - 200$ GeV/c electron beam and should be completed in about 7 accelerator shifts.

The calibration constants α_i of each lead-glass block i of the calorimeter may be determined by recording a large number of showers covering completely its surface. An ideal procedure is to position the electron beam on the center of each block. This requires a very well collimated beam and is time consuming. A more rapid and practical solution is to callibrate "in-flight" by scanning continuously the calorimeter, block after block, such that each block sees a few hundreds of showers. In this case the calibration constants may be found by solving the set of linear equations

$$\frac{\partial}{\partial \alpha_i}\left[\sum_j \left(\sum_i A_{ij}\alpha_i - E\right)^2\right] = 0 \tag{2}$$

where E is the electron energy, A_{ij} is the measured amplitude, the index i is the block number and the index j is the event number.

Alternatively one may callibrate the calorimeter by exploiting the reconstructed $\pi^0 \rightarrow \gamma\gamma$ invariant mass

$$M = \sqrt{2E_1E_2(1-\cos\theta)} \tag{3}$$

where E_1 and E_2 are the measured energies of the two photon showers and θ is the opening angle [6]. Due to the large cross section of the above reaction this procedure may be carried out anytime during data acquisition, allowing to double-check the light monitor system. Its precision is limited however by the energy and position resolution of the calorimeter.

2.4 Monitoring procedure

2.4.1 Tracking calibration constants

The essential task of the light monitor system is to track the callibration constants α_i for each lead-glass block in the periods between actual callibrations. There are many sources of callibration change: variations of PMT voltages, temperature, presence of the beam and magnetic fields, radiation damage, aging, etc.

Monitoring would be trivial if a perfectly stable light source (i.e. equivalent energy $E = const.$) would be availabile. By firing it at two different times we would have $E = \alpha_i' A_i' = \alpha_i A_i$ from which the new α_i' is easily determined.

Practically the intensity of any light source has variations and this requires to include in the system a reference module (see section 2.2.3) to correct for these variations. Further, the callibration of the RM itself may change and this must be monitored by a light pulse standard (see section 2.2.4).

Let's consider a light pulse sent into the light distribution system which splits its amplitude into various branches. The response of the a particular channel i to the pulse amplitude E_i, the response of the RM to the pulse amplitude E_{RM} and to the LPS pulse amplitude E_{LPS} may be written as

$$E_i = \alpha_i A_i \tag{4}$$

$$E_{RM} = \alpha_{RM} A_{RM} \tag{5}$$

$$E_{LPS} = \alpha_{LPS} A_{LPS} \tag{6}$$

for a particular time. We now make the following assumptions:

1. the RM callibration constant is the same for the light pulse and for the LPS, i.e. $\alpha_{RM} \equiv \alpha_{LPS}$, true if these two sources are very close to each other and have the same light collection efficiency,

2. the E_{LPS} light amplitude is constant in time,

3. the ratios E_i/E_{RM} are constant in time, which requires a very good mechanical stability of the light beam and of the light distribution system.

Under these conditions we may write the above equations at time t and at time $t+\Delta t$ and after reductions we find

$$\alpha(t+\Delta t) = \alpha(t)\ \frac{A_i(t)}{A_i(t+\Delta t)}\ \frac{A_{LPS}(t)}{A_{LPS}(t+\Delta t)}\ \frac{A_{RM}(t+\Delta t)}{A_{RM}(t)} \tag{7}$$

which allows to track α_i in time on the base of the system response to the callibration light.

2.4.2 Time delays and trigger simulation

The PMT response to the callibration light fed to TDC modules may also be used to measure precisely time delays between different detectors. This allows precise gate settings for debugging the trigger system, as well as trigger simulations in the absence of the beam (see section 3.2 for a detailed discussion).

2.4.3 Computer control

The light monitor system may be controlled via an IBM-PC computer loosely linked to the main DAQ system. The main program will control the distribution of light pulses to the lead-glass blocks and will read the digitized response. The pulsing scenario will be integrated in the E781 trigger system such as to perform monitoring in a narrow time window during and in between beam bursts.

♣ *We need to determine the monitoring scenario in conjunction with the E781 trigger system. We must also analyse the posibility to correct the gain variations by automatically readjusting the PMT voltages via the computer. The E781 plan may rather be to do corrections in software.*

The raw data must be availabile on-line as tables, histograms and spectra for all readout channels, for example: amplitudes from laser, LED and ^{241}Am light standard, ADC pedestals, time delays between detectors, etc. It will be stored on disk and tape for off-line analysis which will provide for all readout channels:

(i) callibration corrections $\alpha_i(t)$ as a function of time and

(ii) liniarity corrections $\alpha_i(E)$ as a function of energy.

2.5 Measurement of the electromagnetic shower

The purpose of this section is to provide a framework for the measurement of the electromegnetic shower in our apparatus. The present discussion is preliminary, the calculations should be refined in order to reach the necessary precision.

The electromagnetic shower initiated by a high energy charged particle or gamma ray develops in a tree-like structure in which electrons radiate Bremsstrahlung photons, which further convert to electron-positron pairs, untill all initial energy is converted to light and heat. In the lead-glass, a signifcant part of this energy is radiated as Cherenkov light. Since the number of generations in the shower and consequently their total path length is proportional to the initial energy, the number of Cherenkov photons provides its measurement.

2.5.1 Shower characteristics

The precise description of the showers is difficult: analytically it can not be expressed in closed form, and Monte Carlo computations are complex.

A qualitatively correct description of the shower process was given by Heitler. By this model [12, 13], a shower initiated by a gamma or electron with an energy above ~ 100 MeV gives birth during each radiation length X_0 to a new generation of particles each with half the energy of the precursor. The electrons radiate gammas as bremsstrahlung and the gammas convert to electron-positron pairs. The radiation length X_0 is the path length after which an energetic charged particle looses $1/e$ of its energy and is given approximately by $X_0 \approx 180A/Z^2(cm)$ with A the atomic mass and Z the atomic number of the medium. This process stops when the energy of a particles fall below a critical value E_c, when the radiation loss equals the collision loss (ionisation and excitation of the medium). This may be approximated as $E_c \sim 580/Z$ (MeV).

The number of particles in the shower after n generations or at a depth $X(n) = nX_0$ is therefore 2^n and the average energy per particle is $E(n) = E_0/2^n$. Therefore, the shower stops at the depth

$$\frac{X_{stop}}{X_0} = \frac{\ln \frac{E_0}{E_c}}{\ln 2} \tag{8}$$

where the average energy per particle equals E_c.

For practical purposes one must rely on parametrizations on the base of measured data. The longitudinal energy deposition may be parametrized as

$$\frac{dE}{dX} = E_0 \, \frac{\beta^{\alpha+1}}{\Gamma(\alpha+1)} \left(\frac{X}{X_0}\right)^{\alpha} \exp(-\beta \, \frac{X}{X_0}) \tag{9}$$

where X is the longitudinal depth, $\alpha \approx \beta X_{max}/X_0$, $\beta \approx 0.5$ and X_0 is the radiation length. Maximal longitudinal energy deposition occurs at a depth

$$\frac{X_{max}}{X_0} = \ln \frac{E_0}{E_c} - t \tag{10}$$

where t=1.1 for electrons and t=0.3 for photons.

The transverse dimension of the shower is determined by multiple scattering of low energy electrons. A useful unit is the Moliere length $R_M = 21$ MeV X_0/E_c. Measured in this units the transversal extension of the shower is independent on the medium and 99% of its energy is contained within a radius of $3R_M$.

2.5.2 Position and energy resolution

The size of the lead-glass block is chosen such that a sufficient fraction of the shower energy is spread on the neighboring blocks, allowing thereby a precise measurement of the shower position by interpolation (shower profile fit or center of gravity). Evidently, a finer sampling of the shower should enhance the position accuracy, however the reduced amplitude per block leads to larger statistical fluctuations. The optimal solution for shower containment was found as a 3x3 block box. The block size is chosen such that for a central shower a fraction $\approx 80\%$ of the energy is contained on the central block [6]. The achieved position accuracy is typically ~ 3 mm for a central shower, improving by a factor ≈ 2 from the center towards the edge of the block. Typical energy resolution is $\sigma(E)/E \sim 5\%/\sqrt{E}$ where E is in GeV.

2.5.3 Performance of the E781 calorimeters

The construction and testing of the Photon I/II calorimeters was discussed in detail [14]. The main characteristics of the detectors are sumarized in table 1. We only state here the main results. The achieved energy resolutiuon is

$$\frac{\sigma(E)}{E}\,(\%) = 1.2 + \frac{4.7}{\sqrt{E(GeV)}} \qquad (11)$$

essentially independent on the beam position. In the case of 4 GeV electron shower more than 99% of the energy was deposited in a 3×3 block array with 88% in the central block. The position resolution was 2.0−5.5 mm, with the resolution improving from the center towards the edge of the central block.

2.6 Photoelectron calculations

The aim of this section is to try to estimate, from first principles, the expected number of photoelectrons for typical showers. Photoelectron calculations are mandatory in order to understand the system and finally to verify that it has reached the design specifications. In addition, it will teach us how to choose the laser pulse (shape, spectrum, duration, etc.) such that the phototube will not, ideally, distinguish it from a genuine shower. This is a rather old idea followed and partially implemented by several systems aiming to reach the best possible monitoring precision (see [3]).

Consider a typical lead-glass block. An exact solution involves an integral over the shower geometry and Cherenkov spectrum, however a simple estimation of the expected number of photoelectrons N_{pe} may be found as

$$N_{pe} = f_{sc} \cdot f_{lc} \cdot f_{sp} \cdot f_{th} \cdot N_{sh} \qquad (12)$$

where N_{sh} is the number of Cherenkov photons originated from the shower which must be corrected by various detection efficiencies: shower containment in the lead-glass block (f_{sc}), light collection (f_{lc}), spectral efficiency (f_{sp}) and signal threshold (f_{th}).

2.6.1 Number of photons

The total path length of electrons and positrons in the shower may be approximated [12] as

$$L = (\frac{4}{3}\, X_0 + \frac{2}{3}\, s_0)\, \frac{E_0}{E_c} \tag{13}$$

where E_0 is the initial energy, E_c is the critical energy, X_0 is the radiation length and s_0 is the stopping range of electrons at the critical energy. As an example, using the data for SF5 lead-glass from [1] (reproduced in table 2) we find for a 300 GeV shower a total path length of 860 m. Due to the low Cherenkov threshold $\gamma_{th} = 1.25$, the electrons radiate light down to an energy of 640 keV, well below the critical energy of 15.8 MeV.

The number of emitted photons may be estimated using the expression of the Cherenkov spectrum

$$\frac{dN}{dLd\lambda} = 370 \cdot \frac{1}{\lambda^2} \cdot \sin^2\theta_c \tag{14}$$

with

$$\cos\theta_c = \frac{1}{\beta n} \tag{15}$$

where $\beta = v/c$ and n is the refraction index and L and λ are measured in cm and nm respectively. One may find, in particular, the number of photons emitted in the visible range $(300 - 700$ nm) per unit length $dN/dL = 873 \sin^2\theta_c$, or 561 photons/cm if we assume negligible dispersion (n=constant). For our typical 300 GeV shower, this leads to a total of $N_{sh} = 4.8\ 10^7$ visible photons.

2.6.2 Shower containment

Using the relations given above the maximum energy deposition of a 300 GeV shower occurs at a depth of $\approx 10X_0$ (or $\approx$ 23 cm using $X_0 = 2.54$ cm) and is therefore well contained longitudinally in the $18X_0$ long lead-glass block of Photon III/III′ (see table 1). The transversal containment may be approximated by integrating a 2D-gaussian distribution with $\sigma = R_M = 34$ mm over the block 39×39 mm^2 size. The resultant containment is $f_{sc} \approx 0.50$.

2.6.3 Light collection

The main part of the shower is emitted at very small angles towards the phototube. The large refraction index of the crystal ($n \approx 1.67$) results in a large Cherenkov angle $\theta_c = 53^0$ as well as in a small angle of total reflection of only 37^0 relative to the normal to the block wall. Most photons are therefore totally reflected and therefore efficiently collected by the phototube. The light collection is enhanced by wrapping the crystal in aluminum foil such that $f_{lc} \approx 1$. The exact light collection factor f_{lc} is difficult to calculate or simulate, but may by measured experimentally.

The time scale for light collection and the shape of the light burst, as seen by the phototube, are important parameters since they determine the electronic signal.

♣ *We need to have an estimate of the shape and duration of the shower light signal in the lead-glass block in order to model the laser pulse accordingly.*

For the nominal geometry of our lead-glass block, we expect a prompt burst with a rise time of ~ 2 ns, due to photons emitted along the crystal towards the photocatode.

The maximum is then at about 4 nsec, and a tail due to multiple reflections in the crystal extends ~ 10 ns.

2.6.4 Spectral efficiency

Part of the Cherenkov photons are absorbed in the crystal. From those left, only part are converted to photoelectrons, thereby initiating an electronic avalanche in the phototube. The spectral efficency is defined as

$$f_{sp} = \frac{\int \frac{1}{\lambda^2}\, T(\lambda) S(\lambda) d\lambda}{\int \frac{1}{\lambda^2}\, d\lambda} \tag{16}$$

where $T(\lambda)$ is the transmission coefficient of the crystal and $S(\lambda)$ is the spectral response (or quantum efficiency) of the phototube. The spectral window of the system is defined as

$$W(\lambda) = \frac{1}{\lambda^2}\, T(\lambda) S(\lambda). \tag{17}$$

The transmission coefficient has the expression

$$T(\lambda) = \exp[-n_a \sigma(\lambda) l] \tag{18}$$

where n_a is the atomic density, σ is the photo-absorption cross section and l is the light path length, a number which depends on the light collection and thus does not have a simple expression.

Typical curves for $T(\lambda)$ (from [15] similar to ITEP lead-glass), $S(\lambda)$ (from [16] similar to the ITEP phototube FEU-84) and for $W(\lambda)$ are shown in Fig. 6 (a)$-$(c). The $1/\lambda^2$ shape of the Cherenkov spectrum together with the quantum response of the phototube produce a maximum in the spectral window near $\lambda = 420$ nm and and average wavelength of 477 nm. This suggests that we may achieve a better simulation of the physical shower by operating the dye laser in this range. The resulting spectral efficiency in the visible range $300 - 700$ nm is only $f_{sp} = 6.0\%$.

For LED selection, similar considerations apply. For lead-glass that undergoes radiation damage, the glass turns yellow, and the transmission response versus λ changes [17]. To test more sensitively for radiation damage, one may wish to change the operating wavelength. It is therefore convenient to use quartz fibers, which have $\approx 99\%$ transmission above ≈ 380 nm in order to keep the whole wavelength range availabile for the dyes.

2.6.5 Signal threshold

The signal threshold efficiency depends essentialy on the gate setting which limits the ADC charge integration time. For present purposes we assume $f_{th} \approx 1$.

2.6.6 Bottom line

Based on the estimations from sections 2.6.1 to 2.6.5, we expect for our typical 300 GeV shower a number of $N_{pe} = 1.4\ 10^6$ photoelectrons. Such a shower, even if partially contained in a lead-glass block, may lead to PMT non-liniarity.

♣ *We need to check and develop a more reliable method for the photoelectron calculations.*

3 The laser system

The purpose of the E781 electromagnetic calorimeter laser monitoring system is twofold:

1. control the energy callibration constants of 1680 individual lead-glass readout channels over long running periods with better than 1% accuracy,

2. provide precise timing information. Short light pulses sent via optical fibers down-stream simulate particle propagation, thereby allowing trigger simulations in the absence of the beam.

3.1 Concept

The layout of the laser light distribution system, in its present version, is shown in Fig. 7. As mentioned, the system has a tree-like structure in which short and intense light pulses injected by the laser are split and transported via optical fibers to the readout elements, each a lead-glass block coupled to a PMT.

The construction and characteristics of a typical N_2 laser may by found in [18]. The amplitude of the light pulses delivered by the laser is not stable in time. The laser emission has pulse-to-pulse variations of $\sim 3\%$ as well as long term veriations of the average amplitude. In addition, the pulse amplitude decreases with the pulsing rate as much as a factor of 4 from 20 Hz to 300 Hz [18]. In order to provide a normalization we envision a system of PIN photodiodes, known to be stable down to $\sim 0.01\%$ (see [19]), included at several points of the light distribution system. As pointed out before, since only a few channels are used for normalization, the crucial requirement for a correct energy callibration is to guarantee that each light pulse is split between the various channels at ratios which are time independent. This requires a very rigid and reliable mechanical construction.

The laser pulse intensity must also be sufficiently high to supply each channel with a light equivalent as large as 600 GeV; in particular, for the Photon III/III' calorimeters (see an estimation of the photon yield in the previous section). For this purpose, one must ensure sufficient laser power distributed evenly to all readout channels. One must therefore aim to minimize the overall light attenuation and to maximize the coupling efficiency between the various optical elements. As mentioned, it is necessary to provide laser pulses of similar spectrum and shape as those stemming from the Cherenkov burst of the shower to ensure a similar PMT response and thus accurate monitoring (see section 3.3.1).

Conceptually, the photon transport through the system is governed by the Liouville theorem, which essentially states that the product of the space and angular spread is constant. In particular, this implies an increase of the angular spread when funneling light from a thick into a thin light guide. Consequently, for an efficient light transport one must ensure by construction that the condition of total internal reflection is always fulfiled. For a perspective on various constuction solutions adopted in similar laser monitoring systems, see [3].

3.2 Laser position and timing

As mentioned, the very short laser pulse offers excellent timing capabilities. It may be used for accurate gate setings, trigger system debugging, as well as for trigger simulations in the absence of the beam. There are essentially two problems associated with it:

1. laser position,
2. timing resolution.

1. The most natural laser position would be near the target. This is however not convenient due to the much slower propagation (factor $n \sim 1.5$) of the laser pulses in optical fibers as compared with the beam. A possible compromise solution is to install the laser closely after Photon I. In table 3, we compare the calculated delay between the time of the beam and the laser pulse at the calorimeter positions in the particular case of quartz fibers. The laser position may be optimized such as to obtain zero delay in one detector at the expense of the others. Depending on optimization, the laser pulse arrives in the interval $(-17, +28)$ ns relative to the beam. Alternatively and preferably, one may locate the laser close to Photon II and III. One can then synchronize these two exactly with the beam, while Photon I would be out of time. Since Photon II, III are needed for higher energy gammas, this solution is more efficient for light intensity. The only long fiber is the one to Photon I. Although there may be strong intensity attenuation in the fiber, Photon I in any case requires less light. One can also consider operating Photon I only with the LED's.

One must consider also how the light system triggering is incorporated in the global E781 triggering. The delays are very different for the two laser positions considered.

2. A very narrow light pulse injected into a fiber becomes broader at the output [20]. The pulse fwhm at output, or the *timing resolution*, is determined by the relative delay between the various modes of propagation. These increase quickly with the fiber diameter. As an example, in a step-index fiber (constant n of the core), the number of modes is approximately given by

$$N = \left(\frac{\pi d}{\lambda}\right)^2 (n_1^2 - n_2^2) \tag{19}$$

where d is the diameter, λ is the light wavelength and n_1/n_2 is the refraction index of the core/cladding. In a typical 200 μm fiber, there are over 100 000 modes, most of them are supposed to decay shortly after input. To second order, N depends on the core/cladding dimensions and materials.

Very small $d < 10$ μm fibers are essentialy single-mode. In a single-mode fiber the timing resolution depends only on the dispersion caused by its different light speed in the core and the cladding. It increases with the length (l), rms spectral bandwidth $(\Delta\lambda)$, and dispersion δ, approximately by the relation

$$fwhm(ps) = 5.35 \cdot l(km) \cdot \Delta\lambda(nm) \cdot \delta(ps/nm/km) \tag{20}$$

In our case, namely $l = 60$ m, $\Delta\lambda = 20$ nm and $\delta = 3.5$ ps/nm/km, this is a very small effect, which amounts to only ~ 22 ps. The major limitation in using single-mode fibers stems from the difficulty and low efficiency in focussing the laser light into such a thin fiber. A more practical 600 μm diameter fiber has however an inferior resolution of ≈ 3 ns over a typical length of 60 m. However, this may still be adequate for E781 requirements.

In addition, achieving a high timing resolution of the calorimeter requires a very attentive adjustment of the fibers' lengths to the lead-glass blocks, not necessary equal but on the basis of fiber-by-fiber delay measurements due to diameter tolerances. As an example, a similar laser system designed for hodoscope callibration; made of 20 m long optical fibers, with core/cladding of 200/380 μm, attained a resolution of 150 psec [21].

♣ *We need to estimate the timing needs of E781 in order to select the most appropiate optical fibers.*

3.3 The laser light distribution system

One simulates the experiment with time pulses not exactly equal to those of detected particles. The primary laser UV light may be converted to blue light in a dye laser in order to match the spectral sensitivity of the photocathodes. In order to couple the narrow laser beam with the fiber bundle it must be widened by for example an inverted Galilei telescope. A converging lens in conjunction with a mixing rod may be preferred to the inverting telescope. The homogenized blue light is then transmited via the fibers to the front face of each lead-glass module.

The N_2 laser is located inside the experimental area. It is thus less accessible for maintenance during run periods, but it is hard to see another possibility, considering the distance to the counting room.

A fiber can be mounted after a laser beam splitter (near the laser) to provide a pulse to trigger the start detectors of the experiment.

The essential elements of the laser system are organized in a primary and a secondary light distribution stage.

3.3.1 Primary stage

This part is installed on an optical bench near the laser in a light-tight box.

♣ *If timing requirements are not critical, it is convenient to locate the laser and the primary light distribution stage outside the beam area for easy access and servicing.*

Its basic elements are:

1. a laser system (Laser Photonics LN300C) delivering short 4 ns pulses of 250 μJ at a wavelength of 337.1 nm with a variable rate of $0 - 40$ Hz, coupled to a dye laser cell which "colours" it, i.e. shifts the primary UV light to a more convenient spectral domain. Presently we have two dye options:

    (a) blue light (peak at 425 nm, spectral band 408-453 nm) closer to the spectral window in which the PMT views the shower,

    (b) green light (peak at 550 nm, spectral band 473-547 nm) less attenuated in regular (glass, plastic) optical fibers.

    A large variety of low cost dyes, covering the spectral domain $360 - 960$ nm in narrow $\sim 20 - 60$ nm windows, is also availabile on the market, allowing to easily choose (or vary) the system spectral range. In both above cases the wavelength shifting efficiency is about 20%.

    We may easily estimate the number of availabile photons by dividing the energy per pulse to the photon energy

$$E(eV) = \frac{1240}{\lambda(nm)} \tag{21}$$

leading (see section 3.3.1) to 4.2 10^{14} UV photons (and $\approx$ 20% less after the dye). This is a rather high number when compared with a maximum of $\sim 10^6$ photons expected from a shower. It ensures sufficient light for our 1680 readout channels with a safe margin of about 5 orders of magnitude to accomodate the various sources of photon loss (light attenuation in the fibers, optical couplings, light collection, PMT quantum efficiency, etc.).

We note that N_2 lasers of similar power were used before to monitor up to $\sim$ 10 000 readout channels in similar energy domains (see [4]).

2. a semi-transparent mirror diverting $\sim$ 1% of the primary photon pulse into a PIN photodiode. This provides a signal proportional to the pulse amplitude, and may be used for normalization, and trigger timing.
3. a laser beam shutter which allows to remotely turn off the light while keeping the laser under pulsing regime. This could just be the 0% transmission filter, but it may be more practical to have an independent device.
4. a set of neutral density filters which provide the attenuation of the primary light in 12 fixed steps, from total extinction to full transmission. This allows checks of the linearity of the PMT response and of the associated electronics. They are mounted on a rigid wheel and remotely moved via a computer controlled stepping motor.
5. a convergent lens with short $2-4$ cm focal length which focalizes the 2-3 mm wide laser beam into a mixing bar.
6. a mixing bar constucted of quartz which destroys the laser coherence and focalization and produces a homogenous illumination at the exit (see section 4 for an example).
7. a fiber head coupled by variable area light guides to the mixing bar which split and then funnel the pulse light into four fibers at ratios proportional to the equivalent energy of Photon I, II, III and III'. (The ratios must take into account transmission losses to the calorimeters.)
8. thick $\sim$ 1 mm low attenuation optical fibers (quartz). Here we consider two options depending on the laser position:

   (i) inside beam area, requiring four fibers running several tens of meters Photon I, II and III,III',

   (ii) outside beam area, requiring one fiber running $\sim$ 75 m to the beam area and then splitting into four fibers running to Photon I, II and III,III'.

As an alternative to the "mixing bar / fiber head" option, we also consider commercially availabile callibrated pig-tail splitters. In addition, we envision to optionally include before the splitting, a light "pulse stretcher", a device which allows to synthetize light pulses of arbitrary shape. This procedure was found necessary and applied before in order to avoid PMT saturation effects and thereby non-liniarities in particular for large pulses. This is so, since the physical shower pulse can be significantly longer as compared with the laser pulse for equal integrated number of photoelectrons (see [22]).

3.3.2 Secondary stage

This part is located on each of the four calorimeters and has the role to further split the laser pulse (as well as light pulses provided by LEDs) to the individual lead-glass blocks. Its basic layout is shown in Fig. 2 for the particular case of Photon I/II, and was described in more details in section 2.2.

The essential element of the secondary stage is a box, shown in Fig. 3 (a), which has the role to couple light comming form different sources into a fiber bundle running into the calorimeter. The essential requirement of this element is to distribute the light efficiently and homogeneously over the rather large area of the bundle of $\sim 3\times 3$ cm^2, such that each readout channel receives with good approximation the same amout of light. We envision several options which include: optical condenser, large area mixing rod, small area mixing bar coupled to light guides and inverted Galilei telescope. We do not aim for very precise homogeneity since the fibers themselves present variations of transmission. More important is that the split ratios be constant with time.

♣ *We need to construct and test the various options of optical condenser for the light box and choose the one which offers best light coupling efficiency and homogenization.*

4 Laser tests

The object of the tests carried out so far was to estimate the stability of the system described above. For simplicity, we considered only one readout channel; equipped with the nominal TF-1 $42.5\times 42.5\times 340$ mm^3 lead-glass crystal of the Photon I/II calorimeter, and the associated FEU-84-3 photomultiplier. We first describe the experimental setup and then present initial results.

4.1 Experimental setup

The experimental setup consists of the N_2 laser injecting blue light pulses into a mixing bar via a convergent lens (see section 4.3.1 for more details). The mixing bar is directly coupled to a fiber head made of opaque PVC in which three thick optical fibers (a central one made of 2 mm diameter plastic and two lateral ones made of 1.5 mm diameter quartz) were glued and their heads polished. All optical elements, i.e. the lens, the mixing bar, the fiber head and the three fibers were izolated from the room light. The larger fiber was coupled to the lead-glass block and the two smaller ones were coupled to two PIN photodiodes. Only one photodiode was used for the present tests, namely a Hamamatsu S1223 with a 2.4×2.8 mm^2 sensitive area. The lead-glass rod was viewed at one end by the nominal FEU-84-3 photomultiplier, from the other end by a RCA-8576 photomultiplier for comparison, and the light pulses were injected at equal distance in between.

The laser pulsing rate was kept low at $\sim$ 10 Hz to avoid heating of the laser tube and progressive reduction of light output. The pulse intensity was conveniently adjusted using neutral density filters.

In order to have an absolute reference for stability studies we considered two solutions. For reference, we coupled an ^{241}Am radioactive light standard to the lead-glass block. Another reference can be minimum ionizing cosmic ray muons passing through the lead-glass. Their trajectory is defined by requiring concidences between two plastic scintillator detectors located above and below the lead-glass rod.

4.2 Electronics and data acquisition

The electronics was kept at a minimum. For the two PMTs we used a LeCroy HV4032A stabilized voltage supply, which reduces to a very low level any PMT gain variation. The achieved stability, checked by measuring the ^{241}Am peak centroid over long time periods was 0.2%. The signals of the two PMTs were fed without amplification to charge sensitive ADCs. The photodiode signal, much smaller and much more sensitive to environmental noise, was first fed to a charge sensitive preamplifier, then shaped in an amplifier, and finally fed to a peak sensitive ADC. The ADCs were readout via CAMAC by our Pascal data acquisition program running on an IBM PC. For E781, we will use charge integrating ADC's.

4.3 Tests and results

4.3.1 Mixing bar

Mixing bars are widely used to enlarge and homogenize a narrow light beam. The idea is to inject light into a transparent bar at an angle larger than the limit for total internal reflection. When the number of internal bounces is large a rather uniform illumination is obtained at the opposite end. Practically ~ 3 internal bounces are sufficient for a homogenization within a few percent. The performance of the mixing bar may be appreciated qualitatively by viewing the source through it: a large number of virtual sources indicate a good mixing. A convergent lens used at input enhances the number of bounces and improves significantly the mixing.

In order to gain experience we constructed a $5 \times 12 \times 400$ mm^3 plexiglass mixing bar in which laser light was injected via a convergent focal length $f \approx 4$ cm lens. This geometry results in two lateral and a large number of vertical total internal reflections of the photon beam inside the bar. The obtained transverse illumination profile may be seen in Fig. 8 as measured with a 2 mm diameter optical fiber scanning the bar and coupled to a PMT. We notice that illumination decreases at the edges, probably due to the low number of lateral bounces. It is also sensitive to a slight misalignement of the bar to the photon beam. The overal variation of the illumination was $\pm 5\%$. Such a variation is adequate, as the main condition is the time independence of the distribution.

4.3.2 System stability

As mentioned above, the PMT and the PIN photodiode view the same laser pulse. The ratio of their signals should be independent, up to small variations of PMT gain, of any variation of the laser output.

In Fig. 9 we show typical spectra of the photomultiplier (a) and (b) and photodiode (c) signals. The photomultiplier voltages were kept low at 1 100 V and 1 250 V respectively to ensure linearity and the pulse intensity was kept high such that further signal amplification was not required. We increased the statistics such that the statistical error on the peak centroid is below 0.01%, thereby alowing to observe the system stability at the same level.

From the percent rms widths of the peaks, $\sigma(\%) = 100/\sqrt{N}$, one may deduce a minimum number of 14 000, 39 000 and 27 000 photoelectrons respectively. By using our estimation in section 2.6 this is equivalent to a minimum ~ 3 GeV light equivalent, as measured by FEU-84-3.

In Fig. 10 we show the result of monitoring the system over a typical period of one work day. In the middle of this period the system was shut down and then restarted after two hours. We notice the rather large transient of ~ 2 hours in which the laser output decreases before approaching stabilization. This trend is recorded independently by the FEU (a), RCA (b) and PIN (c). After a few hours the laser output continues to decrease however the ratios FEU/PIN (d) and RCA/PIN (e) become stable at the level of $\approx 0.1\%$.

The effect described above may be seen in greater detail from Fig. 11 in which we show the result of monitoring the system over a period of 30 minutes after several hours of operation. The FEU and PIN display a maximal $\approx 2\%$ decrease of the mean amplitude. The maximal variation of their ratio is only $\approx 0.3\%$ with a rms spread of $\approx 0.1\%$.

We conclude that the measured instability is at the same level as the PMT gain variation measured independently.

We are building and testing shaping amplifiers, to give the PIN signals a 130 nsec pulse, compatible with the gate width to the ADCs of E781.

♣ *We need to repeat the stability measurements with the complete system, i.e. FEU-84-3 PMT, PIN photodiode and the ^{241}Am LPS, in order to determine the residual stability level.*

5 Photon I detector LED tests

5.1 General

The Photon I monitoring system consists of the following major parts [24]:

1. a light guide distributon system with LEDs,
2. a reference module of a LED generator,
3. a power supply.

Table 4 summarizes the results obtained with available LEDs. At present two types of light distribution systems were used. All presented numbers below are given as measured with one control phototube.

5.1.1 System type I

The first type has one light guide bundle (total of 6 bundles in Photon I, every bundle has 120 light guide fibers). Each bundle is seperately illuminated by 4 LEDs. Among them are 1 red and 3 green LEDs (HLMP3950, brightness 50 mCd). There is an input for a fiber providing a laser light pulse. Light produced by any of these 5 sources via a light diffusion box (tube) is mixed and transported to entrance of the light guide bundle. LED's are installed inside a thermostabilized box. Every LED is fired by its own generator with output of 80V/50Ω with duration of 15 nsec. By computer command a switching unit fires the LED generators. To control light output from every LED, one compares with light from a radioactive source installed inside the control unit (see below).

There are 24 LED's in the Photon I monitor system of type I (18 green and 6 red LEDs).

An average light amplitude in units of energy deposited in the lead glass block was found to be:

3 GeV for green LED with relative dispersion of ±20%,

40 GeV for red LED with relative dispersion of ±300%.

5.1.2 System type II

The second light guide distribution system has two thermo-stabilized boxes with one red LED inside each (the same type as before) and 5 green ones. There is an intermediate light guide which divides light between three light fiber bundles. There is possibility to install a light guide from the laser. Average amplitude of the LED (over 315 channels) was found to be:

0.8 GeV for green LED with relative dispersion of ±20%,

8.0 GeV for red LED with relative dispersion of ±20%.

5.1.3 Reference module

Both of the above discussed systems are connected via light guides to a reference module consisting of a FEU-84 phototube (with sensitivity of 160 μA/Lumen) and a scinillating crystal of YAlO3:Ce with an implanted alpha-source of ^{241}Am (activity of about 50 Bq). The light source is compact with a peak wavelength of 375 nm and pulse duration of about 120 nsec.

The reference module had two outputs. One output provides a signal to trigger the data aquisition system, other is a standard amplitude analysis analogue output.

The following characteristics were obtained: the alpha-source signal has energy equivalent of 0.75 GeV with resolution of 14% (HWHM). Temperature is controlled in the range of 28 ± 0.2^0C, which gives full temperature instability of the light alpha source of 0.39% per $^0C \times 0.4^0C = 0.16\%$.

5.2 Discussion

According our estimations, the average amplitude of the Photon I monitor light pulse has to be about 20 GeV (about 80% of its dynamic range) and 40 GeV for Photon II. The relative dispersion between the calorimeter channels has to be less then ±20%.

As follows from the results above, the first system (which is using the existing types of LED) is close to required amplitude in the average channel (with red LED 40 GeV for one channel) but has very wide dispersion of 300%. If the dispersion is made within ±20% as required, the average amplitude will fall by factor $3 - 4$ which is not acceptable. Moreover this system will require a combersome system to check LED stability (the total number of LED will be 24). The second system was made as a step to the simplest solution, i.e. one LED for full Photon I. This system allows using available LEDs to control Photon I for present tests and after small improvement to have one (bright enough) LED for the whole detector. We estimate the brightness of the LED to not less then 2000 mCd.

Finally it is shown that any of these systems can provide calorimeter monitoring to control signal level with accuracy of about 0.1%.

6 Project status and planning

6.1 Present status

We briefly describe some of the projects presently carried out at Tel Aviv with the laser pulse system:

1. We optimize the system to give both good time and amplitude stability.

2. We test laser intensity monitor systems based on Si-photodiodes. These have excellent stability and small temperature coefficient. We test different photodiodes. We must still study whether these must be in temperature controlled environment. Good possibilities are PIN-type diodes from HAMAMATSU (types S1223 and S1223-01) with 6.5 mm^2 and 13 mm^2 sensitive area. We optimize the associated preamplifier and shaper in order to obtain short $\sim$ 100 ns signals.

3. We test different light distribution systems. Specifically, we optimize the technique of the "mixing bar", to achive efficient and homogeneous light coupling both at the primary and at the secondary light distribution stage.

4. We construct the primary laser light distribution system as well as the long optical fibers running to the four calorimeters. These will be quartz fibers in order to minimize the attenuation losses for the intended blue light (450 nm) operation.

For testing we are using the data aquisition system described in section 4. We later need to implement algorithms to analyse such monitoring/callibration data and to calculate an answer in the form of corrected callibration constants, and appropriate error messages if the required stability level is not achieved. We need C programs for this purpose. Following these tests, we need to install an integrated callibration/monitoring system at Fermilab.

6.2 Open questions

We collect in this section the open questions highlighted above, which require further discussions and decisions.

♣ *We need to check tabel 1 for accuracy and to complete it with the missing data by further TAU-ITEP-IHEP contacts in order to reach a full picture of the E781 calorimeter system.*

♣ *We need to find more powerful LEDs and ensure that the laser power covers the whole range assigned to each readout channel of the four calorimeters.*

♣ *We need to decide on the need to monitor in burst, to allocate a convenient time slot, and to decide on the exact monitoring schedule.*

♣ *We need to clarify the exact function of the light pulse control module and decide on the most convenient way to integrate the laser in this system.*

♣ *We need to analyze the need to have an additional DC light source for PMT gain measurements.*

♣ *We need to determine the monitoring scenario in conjunction with the E781 trigger system. We must also analyse the posibility to correct the gain variations by automatically readjusting the PMT voltages via the computer.*

♣ *We need to have an estimate of the shape and duration of the shower light signal in the lead-glass block in order to model the laser pulse accordingly.*

♣ *We need to check and develop a more reliable method for the photoelectron calculations.*

♣ *If timing requirements are not critical, and if otherwise practical, we can locate the laser and the primary light distribution stage outside the beam area for easy access and servicing.*

♣ *We need to estimate the timing needs of E781 in order to select the most appropiate optical fibers.*

♣ *We need to construct and test the various options of optical mixing bars for the light box and choose the one which offers best light coupling efficiency and homogenization.*

♣ *We need to repeat the stability measurements with the complete system, i.e. FEU-84-3 PMT, PIN photodiode and the ^{241}Am LPS, in order to determine the residual stability level.*

6.3 Work schedule and responsibilities

Component testing and construction work of the light monitor system will continue at ITEP, IHEP, TAU, and FNAL. According to the Fermilab E781 Experiment Schedule, it must be installed together with the four Photon calorimeters by July 1995 and then fully tested and debugged until the January 1996 run start date.

> ITEP and IHEP are responsible for the LED light source and the secondary light distribution system.
>
> TAU is responsible for the laser, the primary light distribution system, improvement of the light coupling at the secondary stage, and the system of PIN photodiodes integrated both at the primary and at the secondary stages.

The major steps to be carried out at Fermilab are:

1. integration of the laser in the existing LED light pulsing system,
2. installation of the computer driver and of the associated software,
3. testing and commisioning of the complete calorimeter and light monitor system.

We aim to finally reach a global stability of the light monitor system at the level of 0.1% to 1%.

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List of Tables

	Photon I	**Photon II**	**Photon III**	**Photon IV**
Distance (m)	5.283	35.698	47.69	50.99
Energy range (GeV)	$1-20$	$1-50$	$1-500$	$1-100$
Block size (mm^3)	$42.5 \times 42.5 \times 340$	$42.5 \times 42.5 \times 340$	$38.2 \times 38.2 \times 450$	$38.2 \times 38.2 \times 450$
Number of blocks	576	448	328	328
Photomultiplier	FEU-84	FEU-84	FEU-84	FEU-84
Block size (mm^3)	$85 \times 85 \times 340$	$85 \times 85 \times 340$		
Number of blocks	54	210		
Photomultiplier	FEU-110	FEU-110		
Lead-glass type	TF-1	TF-1	TF-1/F101	TF-1/F101
Rad. length (cm)	2.54	2.54	2.54	2.54
Outer size (mm^2)	1360×1105	2380×1105	802.2×611.2	802.2×611.2
Hole size (mm^2)	425×170	510×595	152.2×76.4	152.2×76.4
Light boxes	6	6	1	1
Control module	1	1	1	1
Reference modules	1		2	2

Table 1: Some characteristics of the E781 electromagnetic calorimeters.

Composition (by weight %)	55 PbO, 38 SiO_2, 5 K_2O, 1 Na_2O
Radiation length (cm)	2.36
Critical energy (MeV)	15.8
Refractive index	1.67270
Specific gravity	4.08
Expansion coefficient (m deg^{-1})	85 10^{-7} (from -30^0C to $+70^0$C)

Wave length (nm)	Transmission coefficient 25 mm (%)
340	2
350	27
360	57
370	75
380	85
390	92
400	95
420	97.5
440	98
500	99
700	99.3

Table 2: Some properties of the SF5 lead glass.

	Photon I	**Photon II**	**Photon III/III′**
Detector position (m)	5.283	35.698	46.560
Laser position (m)	Laser delay (ns)		
0.0	-8.1	-54.5	-71.1
8.906	0.0	-11.2	-27.8
11.214	-11.2	0.0	-16.6
14.626	-27.8	16.6	0.0

Table 3: Calculated time delay between the laser pulse and the beam for different positions of the laser relative to the target. The optical fiber is assumed quartz (n=1.458). Propagation times are roughly 3.33 nsec/meter for the beam, and 5.0 nsec/meter for light in the fiber.

LED type	Generator pulse V/Ω nsec	$< A >$ GeV	PMT pulse duration nsec	Colour	Catalogue brightness mCd
521-9500-003	80/50 20	60	60	red	75
HLMP 3950	80/50 60	4.0	250	green	60
521-9503-002	80/50 60	3.0	250	green	50
521-9251	80/50 60	2.0	250	green	50

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