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$PbWO_4$ crystals radiation hardness test setup at the CERN General Irradiation Facility

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Abstract

The CMS PWO crystals irradiation facility installed at the CERN GIF (General Irradiation Facility) is described. The measurement method and corresponding stability issues are discussed. The setup was successfully used in the PWO crystals technology optimisation R&D, results of which are illustrated.

1. Introduction

The Lead Tungstate scintillating crystal stability in the high radiation environment is one of the key phenomena, which will define the overall performance of the CMS electromagnetic calorimeter. The required very good energy resolution - constant term of 0.5% - put a severe limit on the stability of all detector elements, including their radiation hardness. It was found practically very difficult to ensure the absolute radiation stability of the crystals at the production stage and the decision was to admit a certain level of damage, less than 6% for PWO, and to trace and correct all instabilities to the required level by an appropriate monitoring system. This way requires a precise understanding of the radiation damage kinetics, which is particularly important for PWO where the visible damage effect is considered to be a result of the balance of the damage and recovery processes [1].

The following methods of PWO radiation hardness study used so far by the Collaboration, are well suited for the growing technology optimisation:

- A high dose rate side irradiation up to saturation at the standard irradiation facilities (Geneva Hospital, irradiation facilities in Minsk etc.) with the light output and optical transmission measurements in the laboratory before and after irradiation. This method gives a reliable information about the overall crystal quality, but the data on damage and recovery kinetics are not available. In case of a fast recovery the crystal hardness is overestimated due to a certain time between the end of irradiation and the start of the measurement, needed to bring crystals from the irradiation facility to the laboratory.

- A low dose rate front irradiation with an on-line photo current registration by a HPMT (CERN TIS facility). The method gives a high precision information about the visible light yield damage kinetics. The limit of this method is that only the front part of the crystal of the depth of 2-3cm is irradiated, hence the method is insensitive to the longitudinal crystal quality non-uniformity.

- A low dose rate side irradiation with short interrupts for the on-line light output measurements. The method gives reliable visible light yield damage data with some limited kinetics information: interrupts of irradiation cannot be too frequent, typically once per half an hour. This method is also limited by the precision of the light yield measurement, typically ±(0.2-0.3) ph.e. for about 10 ph.e. signal, provided by 1.2 MeV photons from ^{60}Co

- The low dose rate side irradiation with the on-line transmission measurement at several wavelengths (setups at COCASE facility [2] in Saclay and GIF facility at CERN). This method consists of the measurement of the transmission for the light injected into the crystals instead of the scintillation light output of the previous methods. But once the PWO scintillation mechanism is not damaged under irradiation [3], this measurement is equivalent to the light yield measurement. The advantages of this method are the high precision, possibility to test several crystals in parallel, detailed information on the damage kinetics.

The mass production and construction phase requires another type of crystal radiation hardness measurements: a sampling control of the produced crystal (at least several percent,

10% in the best case, which means 60 000 x 0.1 = 6000 crystals in total during 5 years) and a good control of the radiation damage dynamics: dependence of the visible damage on the collected doze, recovery, correlation of the light output damage and transmission loss at the light monitoring wavelength, including crystal-to-crystal variation of all these parameters.
The transmission loss at several wavelengths measurements fits well to these goals, contrary to the other methods mentioned above.

2. The method

The measurement method is related to the PWO radiation damage model, described in [1].
The model is based on the facts that:

- the scintillating centres are not damaged by irradiation, hence
- all visible light yield damage is connected to the transmission degradation;
- the transmission damage is proceeded via creation of the absorption bands, position, width and relative intensity of which depend on stoichiometry, impurities and details of the growth technology;
- the absorption centres recovery has a fast component with different time constants for each absorption band.

Finally, the PWO crystal radiation damage is considered as a complex dynamic process of the absorption bands creation and termination. The measurement method adequate to this process is the control during irradiation of the crystal transmission as a function of wavelength or, at least transmission at several wavelengths connected to the most essential absorption bands.
The fig.1 presents the sketch of the set-up.

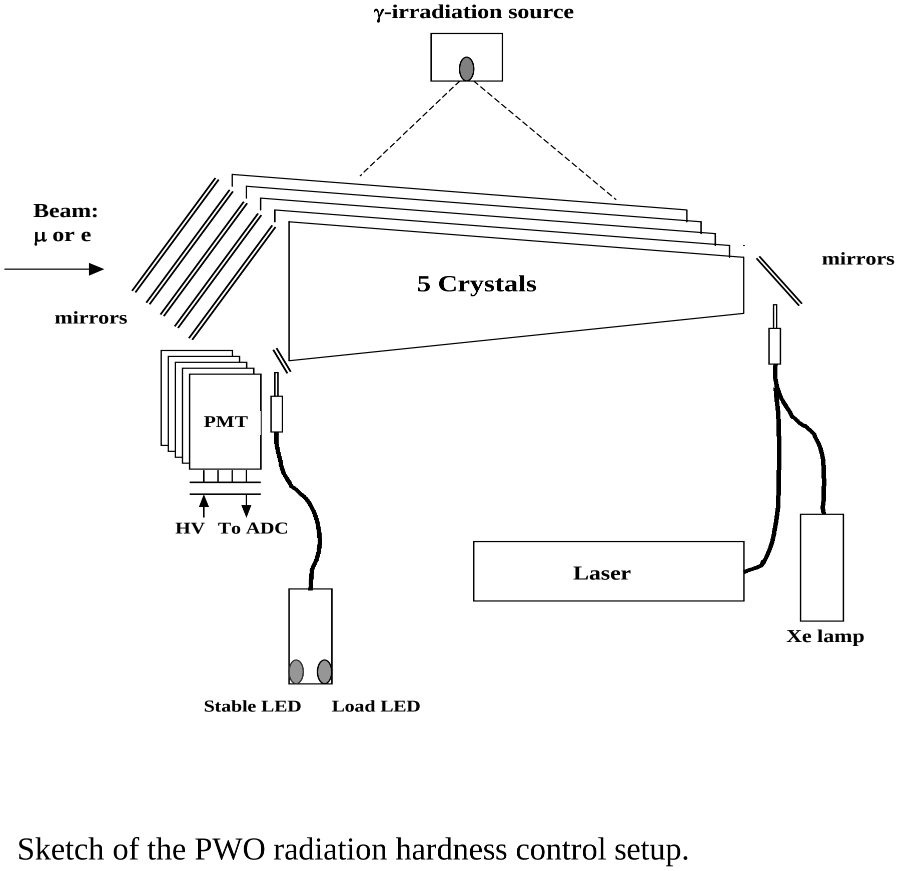

Fig 1. Sketch of the PWO radiation hardness control setup.

2.1 Irradiation source.

The effect of radiation damage may depend on the irradiation particles nature and energy. Ideally the test irradiation conditions should reproduce the ones expected during LHC operation, which are essentially irradiation by a mixture of low energy pions, photons and neutrons [4]. But as this kind of irradiation is difficult to obtain and as the composition and the components energy spectra are different for the different locations in the ECAL, it looks reasonable to study ECAL components hardness for all types of irradiation and for different energies separately. The most essential damage of PWO crystal is supposed to be produced by photons. The model [1] predicts that the damage effect should not depend on the irradiating particles energy but on the collected dose and the dose rate.

The CERN GIF facility, commissioned in 1998, is dedicated for the radiation hardness measurements of the LHC experiments equipment. It consists of the Cs^{137} gamma source situated at the end of the X5 beam line of SPS.

Relevant gamma source parameters:
- γ energy: 0.662 MeV;
- activity: 780 GBq;
- effective dose rate at 50cm from the source: 15 rad/hour (dose rate predicted for ECAL barrel);
- opening angle: 20 degrees (5 full size crystals can be irradiated at a time in 50 cm from the source, i.e. at a dose rate of 15 rad/hour).

Relevant X5 beam parameters:
- beam energy: 5 to 250 GeV;
- particles types: electrons, pions, muons;
- maximum beam intensity: depend on energy and particle type; for example, $5x10^7$ for 100 GeV electrons, $3x10^6$ for 50 GeV pions;
- beam spot: typically $20x20mm^2$.

So, for CMS ECAL the GIF facility provides possibility to irradiate simultaneously 5 crystals at the Barrel ECAL typical dose rate and to make gamma irradiation and beam measurements at the same time using the same setup.

2.2 Light source(s).

The crystal optical parameter really essential for the ECAL performance is the transmission of the scintillating light. So, it would be natural to excite PWO scintillation (by electrons from the β-source or by the high energy beam particles) or to simulate PWO scintillation spectrum: a wide gaussian-like distribution with a maximum around 450nm and a width of about 100nm. But, at least at the R&D stage, it is very useful to check transmission damage wavelength dependence with some 10nm precision, because, according to the damage model, different impurities manifest themselves by creating characteristic absorption bands and these bands presence and their relative intensity give a very useful information for the growth technology optimisation. It is also clear that by convolution of the relative damage measured at several points covering the scintillation spectrum and the spectrum itself; one can easily estimate the transmission damage for the scintillating light.

A special light source was built for the PWO radiation hardness measurement. It consists of a Hamamatsu L2360 Xe lamp, a light beam shaping optics and a computer controlled monochromator, designed to be used in a spectrophotometer (fig.2).

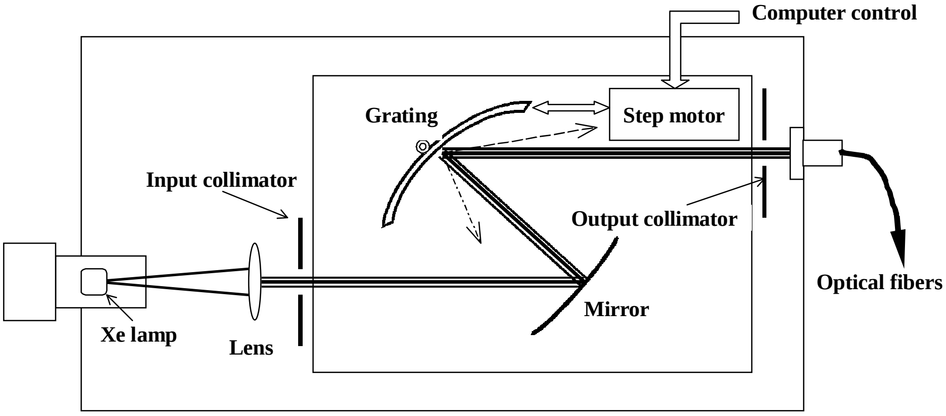

Figure 2. Sketch of the variable wavelength light source

The variable wavelength light source parameters:

- wavelength range: 300-1000 nm;
- wavelength selection precision: ±1nm;
- selected band width: is defined by the output collimator slit, 10nm in the present version;
- wavelength tuning speed: 3nm/sec.

As the Xe lamp used as a primary light source has about 10% pulse-to-pulse instability, the light output has to be monitored.

The LED-based stabilised light source [5] was used for the overall system stability monitoring. It contains a Nichia blue LED with a relatively wide emission band, peaked at 460nm, which is in the range of the PWO emission and fits well to the used photo detectors sensitivity. The measured light output stability of the source is better than 0.3% for 48 hours of operation (sigma of the distribution of the mean values for 1000 pulses, the measurement precision was limited by the test equipment stability).

2.3 Photo detector(s).

As the visible transmission damage may be sensitive to the light collection, a realistic light collection scheme should be used. It includes the crystals coating and the photo detectors. But ECAL basic photo detectors, Hamamatsu APD for the Barrel and VPT for the Endcap, are still the subject of R&D. Although some test samples are available, it seems not practical to use any of them for the PWO radiation hardness control: the photo detector has to be well understood to avoid extra uncertainties.

A widely used and very well studied photo detectors – vacuum photomultipliers (PMT), are used in the setup. A very important advantage of PMT – practically zero radiation damage by the low energy photons, which is generally not the case for the silicon devices.

The Philips XP1921 PMT, selected for these measurements, has 19.2mm maximal external diameter, which fits well to all ECAL crystals dimensions and bialkaline photo cathode with a spectral range 300 to 650nm.

It have to be noted that PMTs have very well known long- and short-term instabilities [6], which require a special attention for the stability measurements.

2.3.1 The XP1921 stability.

The first essential effect to be taken into account is a slow variation of the PMT gain after High Voltage is switched on. “Slow” means a time constant of several hours. The absolute value and the sign of the gain variation are different for different PMT types [6].

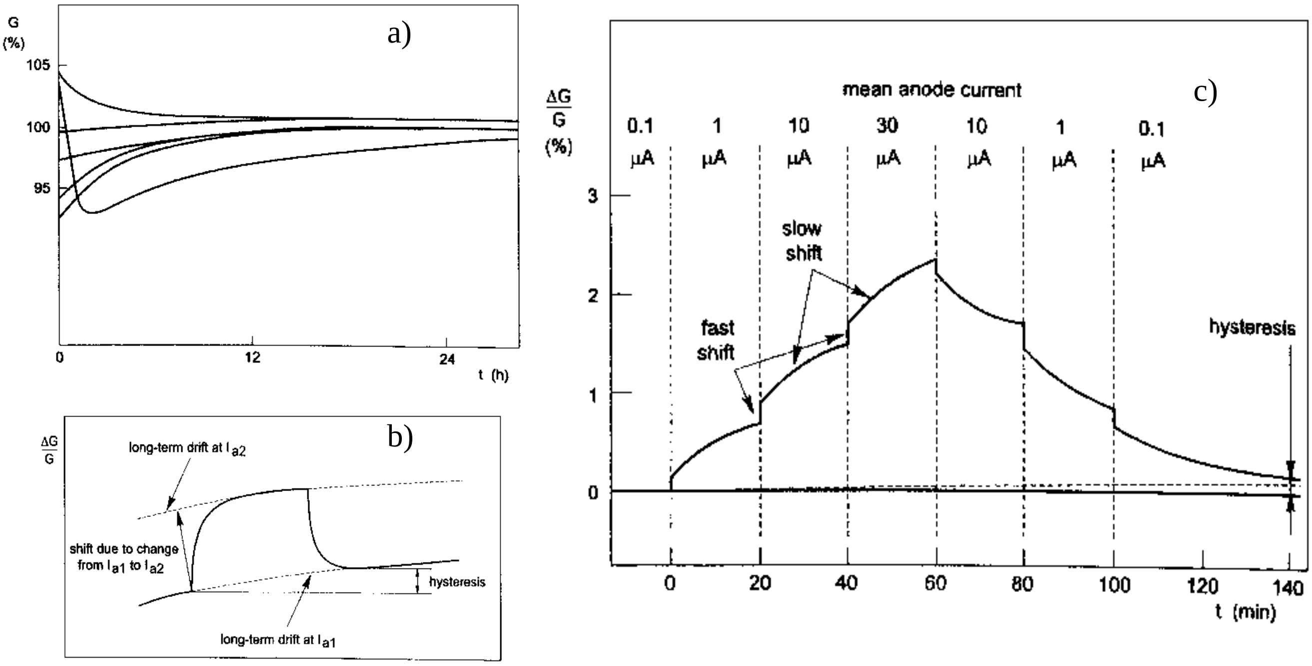

Figure 3. PMT stability figures taken from the PHILIPS book “Photomultiplier tubes, principles & applications”. a) examples of the gain initial low-current drift; b) long-term gain drift and short-term shift due to change of operation conditions; c) example of the gain change as a function of mean current and time.

The gain drift by (5-10)% during about 10 hours (fig.3a). After that no significant gain variation is observed. The recommendation of the PMT Producer is to stabilise the system at the full working conditions, with PMT powered by high voltage, during10-12 hours before the start of stability measurements.

The more important effect is the gain variation due to the mean current. Up to about 3% of the maximum mean current, 6μa in the case of XP1921 (Imax = 200μa) the gain remains stable. For the mean current above that value the gain rises up and stabilises at a level dependent on the mean current value (fig.3b,c). The time constant of this process is several hours. A 15Rad/hour irradiation excites PWO crystals and produces a PMT mean current of (30-40)μa, depending on the crystal light yield. This current value is well above the “stability threshold” and the PMT gain increases by 10-15 % after the start of the irradiation (fig.4b). The value of the gain variation and the time constant are varying from one PMT sample to another. Hence, the gain of each PMT has to be monitored during the measurements.

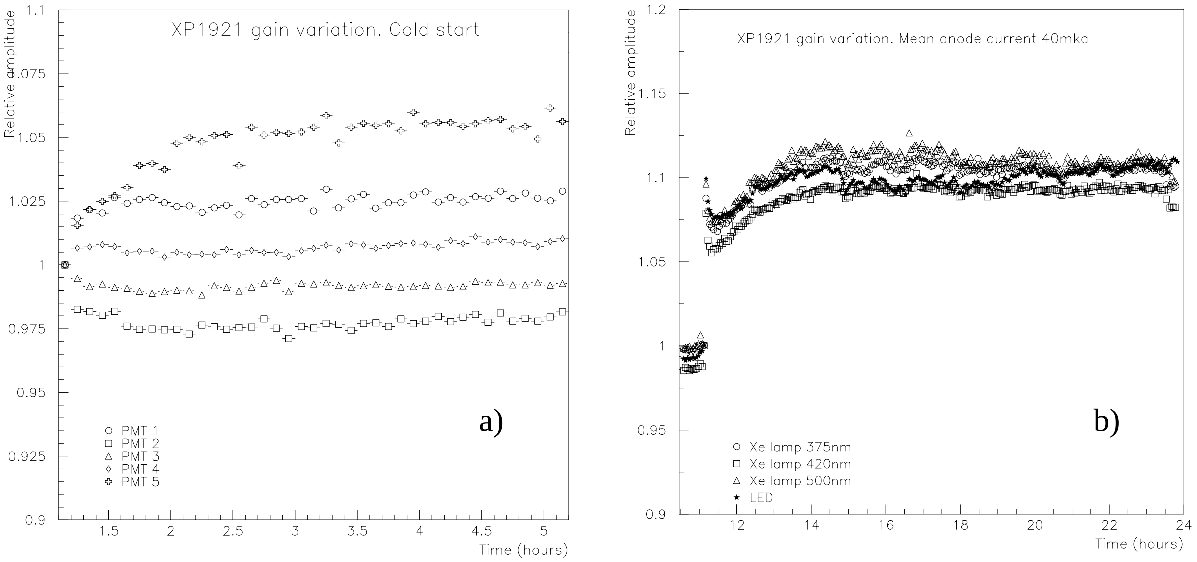

Figure 4. a) XP1921 gain low-current drift;
b) XP1921 gain variation due to the 40µa mean current created by the “current LED”, simulating irradiation conditions (measured with LED and Xe lamp signals).

To avoid a strong PMT gain variation just after the start of irradiation, when the most significant damage effects are expected, a special PMT training is applied: the illumination of the PMT photo cathode by a high frequency low amplitude LED pulses (“current LED”). The “current LED” frequency and amplitude where tuned to provide roughly the same PMT mean current as 15Rad/hour irradiation. After 24 hours of such a training PMT gain is stabilised and the irradiation start produced only a small additional gain variation , which is monitored to the 0.5% by the stable LED signal.

2.3.2 The light collection.

The XP1921 photo cathode has an effective diameter of 15mm. It covers about 27% of the back surface of the Barrel ECAL full size crystal. The photo cathode mean quantum efficiency for the PWO scintillating light is about 20% (from 26% at 400nm to 16% at 500nm). The detected scintillating light signal corresponds to about 10 photoelectrons per MeV – more than enough for a precise beam measurements at the energies above 1 GeV. The transparency of the crystal is rather high and the crystal acts as a good light guide for the monitoring light injected through the front face. This allowed to use optically less efficient but practically much more convenient scheme of the light injection and collection via mirrors placed at 45 degrees to the crystal front and back surfaces (fig.1). This scheme exclude also mechanical contact of the tested crystals with photo detectors and monitoring light injection fibres and help to avoid scratching of rather soft PWO crystals during mounting and dismounting of the setup.

2.3 Temperature control.

Although the temperature is not very important for the “standard” radiation hardness measurement because PMT gain and quantum efficiency are practically not sensitive to the reasonably small temperature variation as well as the crystal transmission, the level of the damage-recovery equilibrium and hence the observed radiation damage depends on the temperature [1]. In addition, during the electron peak position measurements at X5 beam a good temperature stabilisation and control are required. For these reasons the test setup is equipped with a temperature stabilisation and control system.

The temperature stabilisation system is essentially a massive block of cupper with pipes for circulation of the water thermally stabilised by a special unit and a thermo-isolating walls around the test box. The control is performed by thermo-sensors inside the test box read out by a dedicated unit.

3. The setup

An artistic view of the GIF setup is presented in fig.5. All measurement equipment is mounted inside an aluminium box of 700x500x400mm^3 placed on a chariot equipped with the remotely controlled horizontal and vertical displacement mechanism. This mechanism allows to position the test box for the Cs^{137} irradiation and the beam measurements alternatively. The height difference between Cs^{137} irradiation position and the position when the beam hits the central crystal is 650mm. The vertical displacements are performed by hydraulics, which guarantees a smooth start/stop, required by the optical connections stability.

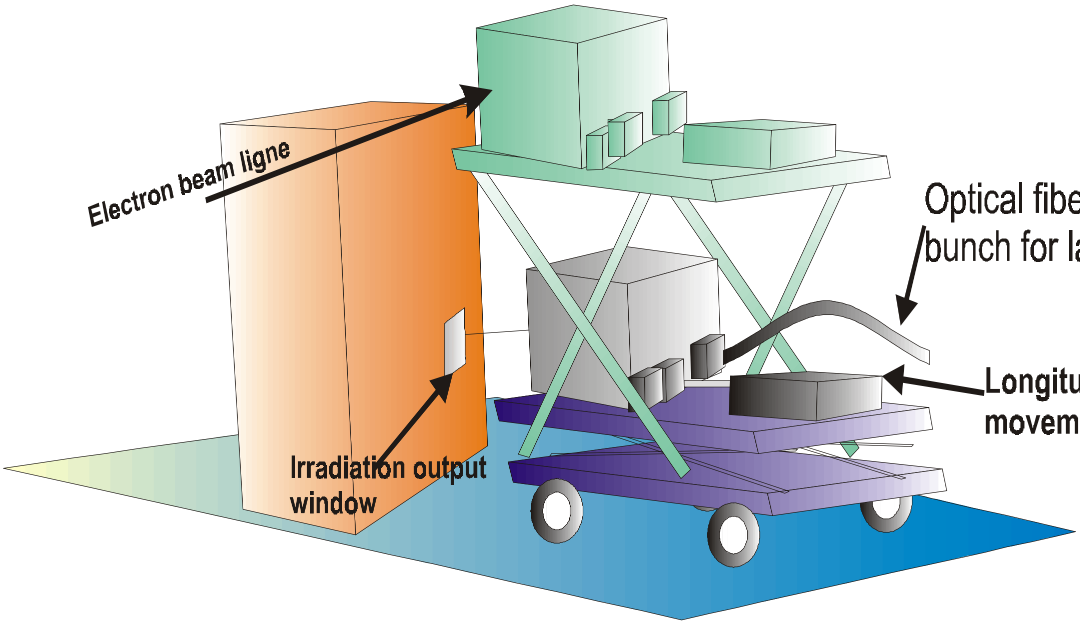

Figure 5. General structure of the setup.

The size of the test box is defined by the available space in front of the Cs source window and is rather small which means a very dense equipment mounting. The sketch of the equipment placed inside the box is presented in fig.6.

Five crystals under test are placed on shelves attached to a massive cupper plate, thermally stabilised by the circulating water of a “Bio-block Polystat” thermal stabiliser. A set of 10 AD590 thermo- sensors are placed inside the setup: 5 are attached to the crystals on the photo detector side, 3 – to the top, medium and bottom crystal at the opposite side, one measures the air temperature inside the box, one - the temperature of the control channel placed inside the box. The box is covered by a passive thermal screen made of 5mm PVC and 20mm plastic foam. The crystal temperature stability is about ±0.1 degree for a 48 hours measurement cycle.

A block of 5 mirrors is placed behind the crystal back surfaces. It is made as a mechanically solid unit, easily removable because it has to be removed for each mounting and dismounting of a crystal set.

Five PMTs with their HV dividers are also mounted as a solid mechanical unit at 90 degree to the crystals. Each PMT has an individual power line connected to the High Voltage distributor in the counting room and 4 booster voltages are common for all PMTs.

Two quartz fibre-bundles are transporting the monitoring light from the light sources to the front and the back surfaces of the crystals. The light from the variable wavelength source is injected through the crystal front surface by a fibre placed normal to the crystal axis via a small mirror at 45 degrees. A second fibre is transporting the LED stabilised source light, used for the gain monitoring, right to the PMT photo cathode via a properly inclined mirror. The light of the “current LED” used to generate a PMT mean current is mixed with the stable LED signals. Both light sources are placed outside the test box.

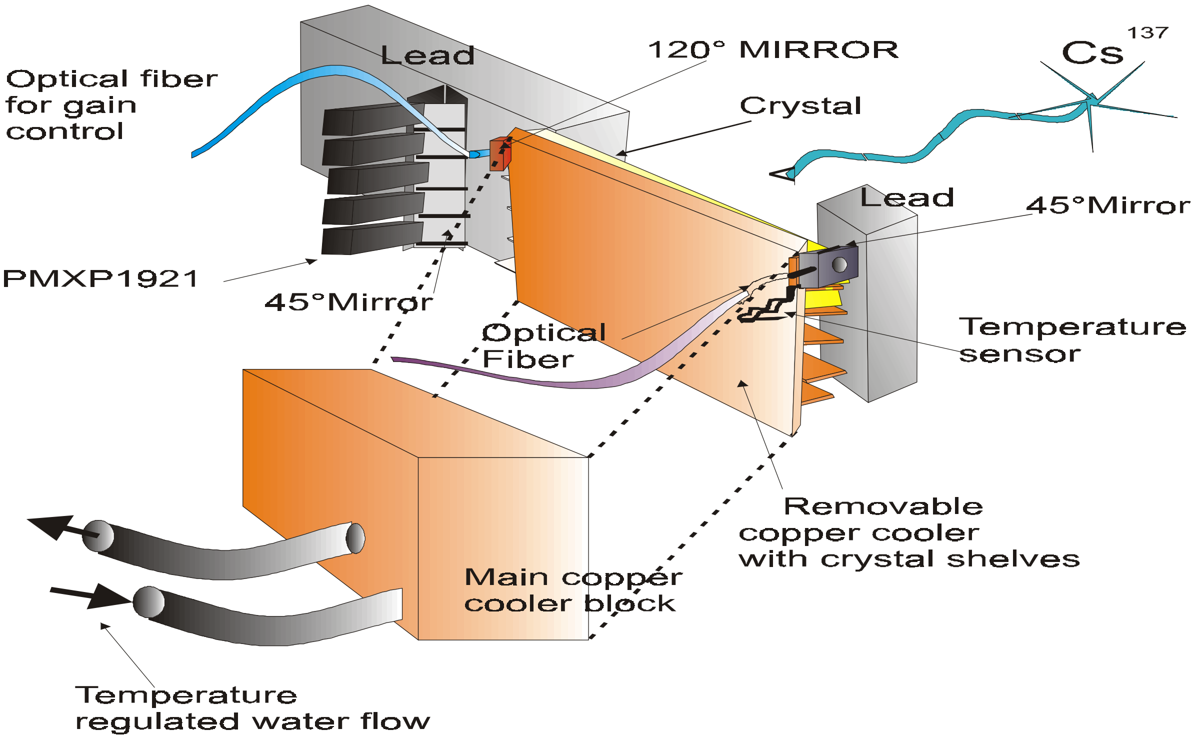

Figure 6. The sketch of the internal test box equipment.

All input and output connectors for power and signals are mounted on small metal boxes attached to the test box. The choice of connectors was driven first of all by stability requirements. BNC and SHV connectors where selected for the internal part of the box, although it lead to some space problems. BURNDY connectors are used for all external cables: a 64 pins one for the signals, a 26 pins one for the high voltage and a 6 pins one for the booster voltages. This makes the connecting/disconnecting of the cables in the irradiation and tuning position fast and reliable (see section 4 for the measurement procedure details).

3.1 High Voltage.

The PMTs are powered by a HEINZINGER HNC 2500 High Voltage power supply at about 1000V. The voltage stability is better than ±1V. With the HV base of the Phillips type B [6] (high linearity) PMTs should be linear within ±2% up to the anode current 80mA. The anode current did not exceed 50mA during all measurements. The last 4 PMT dynodes are connected to four booster high current power supplies OLTRONIX B605. Application of the boosted voltage is improving the PMT linearity and the short- and long-term stability. Finally, the PMT signal linearity is better that 1% (peak-to-peak value, correspond to $\sigma \approx 0.2\%$)

3.2 Readout electronics.

The PMT signals were delivered through 70 m coaxial cables to the counting room where they are digitised by a charge integrating ADC. Two types of ADC are used:

1) a CAMAC ADC produced by NA12 experiment, based on Lecroy MQT200 charge integrator, 13 bits range, 100 fC/count sensitivity;

2) a Lecroy 1182 VME ADC, 12 bits range, 50 fC/count sensitivity.

The first one is useful when a high signals range is needed. The second one was found more stable and is used for most of the measurements.

The temperature probes are readout by a dedicated VME unit produced by LAPP. The measurement precision is 0.1 ^{0}C/count.

The readout electronics include also a 8 channels CAMAC TDC Lecroy 2228A, used for the SPS beam wire chambers readout during the beam measurements, a 12 channels CAMAC pattern unit Lecroy 2341 and a 8 channels CAMAC input/output register.

3.3 Data Acquisition system.

The data acquisition system consist of:

- a PC, running Windows NT with LabView™ Instrumentation package, National Instruments PCI-VME interface;
- a VME crate with National Instruments MXI-2 and CES CAMAC branch driver CBD 8210 ;
- a CAMAC crate;
- 2 NIM crates with the trigger and service electronics.

All DAQ software is developed in the standard LabView framework which make it transparent for any LabView expert and easy to modify and upgrade. The DAQ schematics and the control panel are presented in fig.8 and fig.9 respectively. The current version of DAQ supports 6 different trigger types: Pedestal, LED, Test Pulse, Laser, Xe lamp and Beam, which can be arbitrary mixed. It provides event readout and saving on the local disk. The readout time, including disk writing is less than 2.5ms per event.

The system provides also some minimal on-line control: amplitude spectra and stability graphs for each ADC channel, temperature stability graphs, TDC values distributions. There is a separate set of graphs for each trigger type.

But once the data manipulation tools are rather poor in the standard LabView, a more powerful control is done by a task running on Unix work station connected to the DAQ via generic LabView software socket.

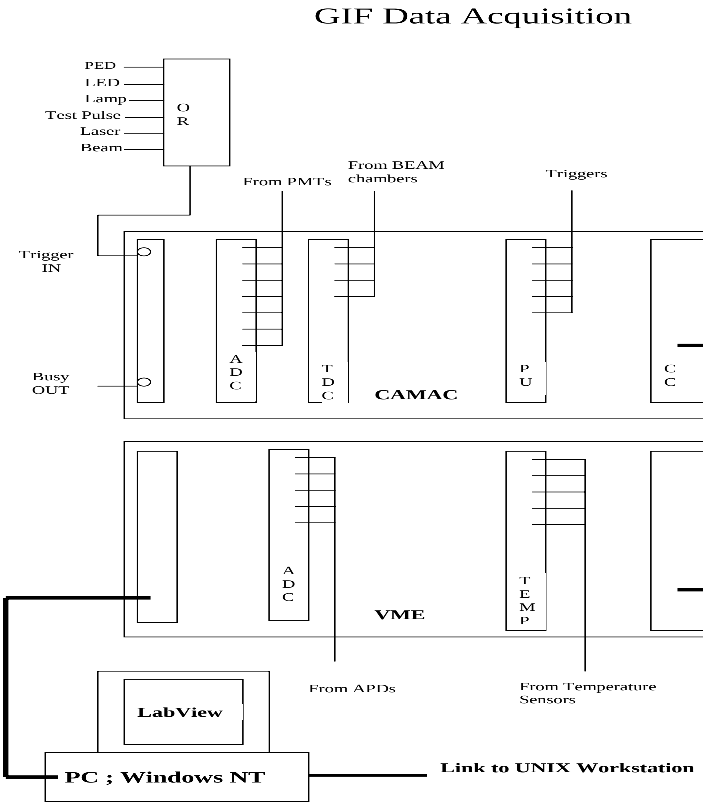

Figure 8. GIF Data Acquisition system diagram.

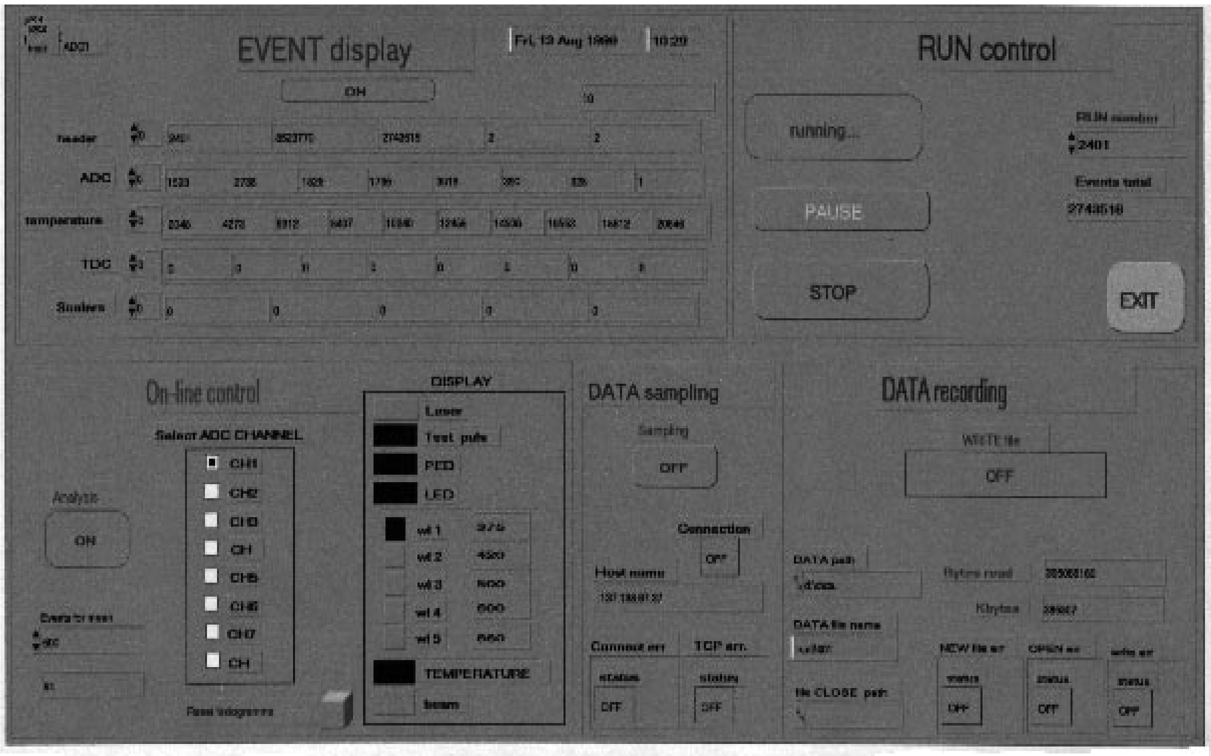

Figure 9. GIF DAQ control panel

4. The measurements

The ECAL GIF test zone has essentially two sites: one near the Cs source side window, where irradiation is taking place, and another outside the irradiation zone near the exit door. Both zones have a full set of signal and control cables arriving from the counting room. The test equipment is mounted on the chariot, which can be easily moved from one site to the other. The site outside irradiation zone is used for the setup tuning, stability control etc. As soon as all equipment is running well one have to disconnected all cables, ask access to the irradiation zone, move the chariot to the irradiation position and connect all cables. This procedure takes normally 5-10 minutes.

The setup tuning outside the irradiation zone is needed because CMS ECAL is not a primary user of GIF facility and the interrupts of the irradiation performing by the other groups have to be as short as possible.

4.1 The measurement cycle.

Taking into account all PMT stability issues, discussed above, the measurement cycle is set conducting in the following way:

1. **Stabilisation**: minimum 24 hours of the full setup operation in the irradiation position with the irradiation source off and with “current LED” pulser producing about 40μa mean current in all PMTs. The PMTs stability is traced and decision to start irradiation is taken based on the real stability pattern. If PMTs were not under high voltage long time before the run start, stabilisation can take 48 hours, if the pause was 1-2 hours only (typical time needed to replace crystals and check all sub-systems), 24 hours is enough. The PMT gain control is always working during stabilisation run and the first off-line data consistency check is the test of stability of the corrected Xe lamp and Laser signals.
2. **Irradiation**: 48 to 70 hours of Cs^{137} irradiation at a dose rate of 15 rad/hour. The “current LED” remains ON during this run to avoid PMT gain jumps at an eventual source ON/OFF.
3. **Recovery**: minimum 24 hours of the data taking with the source OFF. The aim of this run is first to cross-check the setup stability and second to detect the fast crystals recovery component, if any. This component, with a time constant of the order of hour, is the most dangerous one for the ECAL stability and should not appear for the good crystals.

4.2 The data analysis.

The off-line data analysis was done in two steps.

1. The raw data decoding, quality tests, calibrations, pedestal stability test and subtraction. The check of the two control channels signals correlation. Checked and calibrated data are re-written in a n-tuple format for a further analysis.
2. Production of the stability plots. First, the signals from each PMT are normalised to the stable LED signal to correct the gain variation. Then Xe lamp signals for each wavelength are corrected using the control channels information. The same procedure is applied for the laser signal when it is used. The temperature variation during practically all measurements was less than $\pm 0.1^0$C, hence no special correction is needed.

The stability plots are essentially the normalised light signal versus time. The actual collected dose rate for each crystal is calculated on the base of the special measurements with thermo-luminiscent foils. The relative dose rate map is presented in fig. 9.

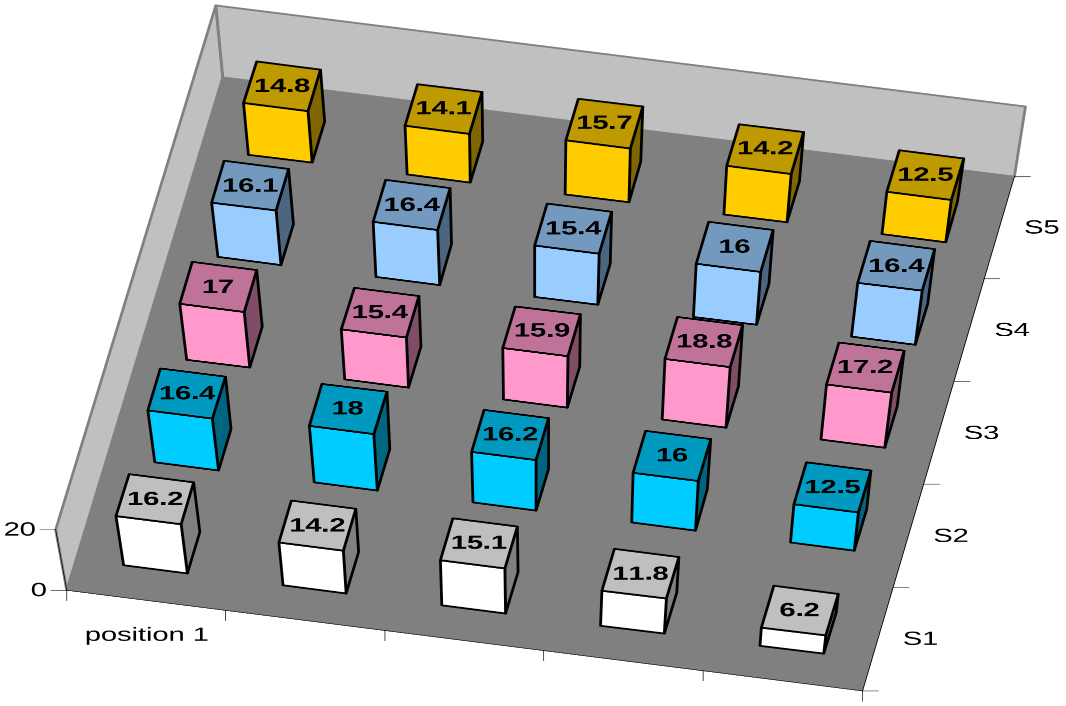

Figure 9. The dose rates along each of 5 crystals, measured with the thermo-limuniscent foils. S1-S5 indicates crystal 1 to crystal 5 positions. The vertical scale is in Rad/hour. The measurement precision is ± 10%.

4.3 The systematic errors.

The instrumental systematic errors where evaluated by the comparison of the results of several irradiation of the same crystal set. Five crystals where selected for these measurements. They where irradiated 4 times with the ECAL-standard thermal annealing after each irradiation. The crystals where placed at different positions in the setup for each irradiation. The systematic errors of the crystal transmission loss measurement where found to be about 0.5% for all channels. These errors do not include the dose rate variation which have to be corrected separately.

5. Some results

17 irradiation, 5 crystals each were performed at GIF by now. In most of the cases it was a part of the PWO technology improvement R&D program. Specially selected samples were irradiated and results, after detailed analysis, have been transmitted to the Producer and to the relevant crystals research groups involved into the R&D. An example of the good Nb doped crystal plot is presented in fig. 10. The crystals quality was rather high but the damage is relatively large and has a significant crystal-to-crystal variation. The 5% damage effect at 420

nm should correspond, according to the H4 beam measurements, to about (8-10)% decrease of the electron peak position. The result of the R&D was production of the double-doped crystals having much lower and much more uniform value of the transmission loss due to the radiation damage (fig.11).

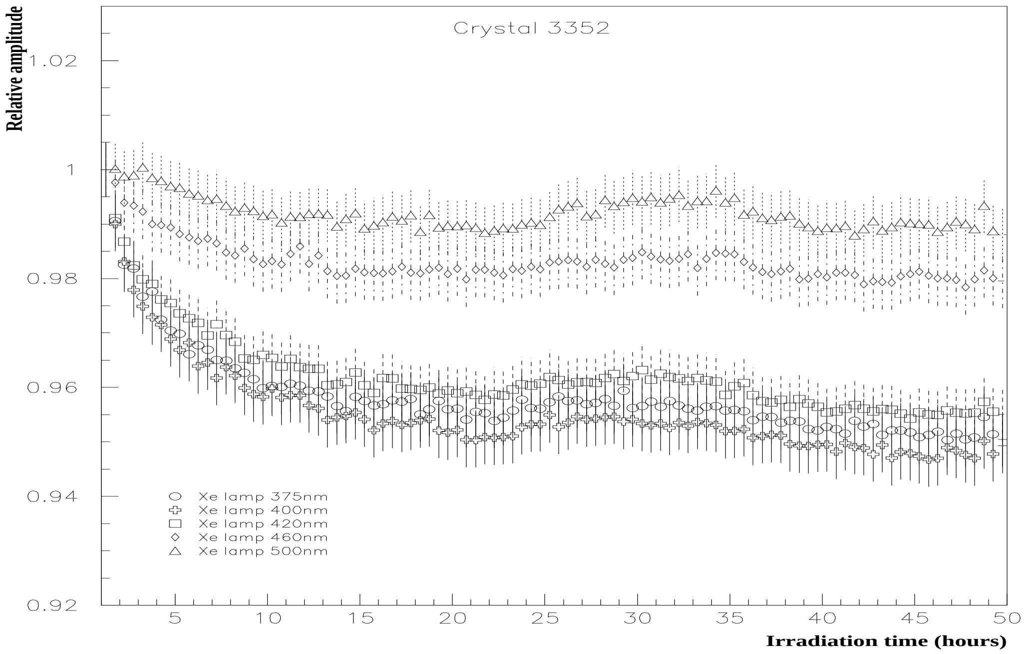

Figure 10. The optical transmission damage of the pre-production Nb-doped crystal # 3352.

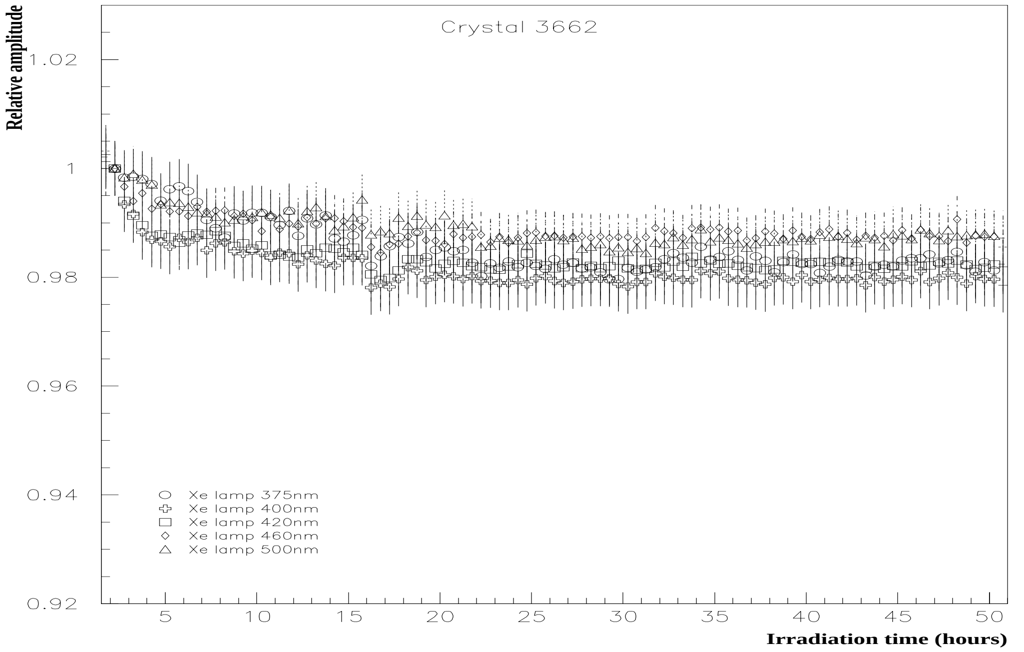

Figure 11. The optical transmission damage of the double-doped crystal # 3662.

Acknowledgments.

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