NPS Calorimeter Curing System

All known crystals suffer from radiation damage. The most common damage phenomenon is radiation-induced absorption (reduction in crystal's light attenuation length). Studies show that the PbWO4 crystal scintillation mechanism is not damaged up to 2.2 Mrad radiation dose. The radiation damage of crystals show clear saturation. Both, transmittance and light output are stabilized after initial dosage of a few tens to 50-100 krad. Level of damage at saturation has dose dependence. It also depend on composition of the crystals, type and amount of doped material. Depending on these factors most effective wavelength for curing may vary from 400 nm to 600 nm.

Crystals under room temperature spontaneously recover transmission (this is due to so called room temperature thermal annealing) but it will take very long time. Recovery of PbWO4 transmittance irradiated at 30 rad/h in equilibrium will take more than ~20 days. A fast, effective and practical way is simulated recovery with light, the so called, optical bleaching. This can be done in-situ without major changes in detector configuration.

Studies the radiation condition in Hall C show that during planed experiments the accumulated radiation dose may exceed ~100-200 krad. To keep calorimeter's performance at the required level a light curing system will be constructed and periodically used between different kinematic settings of the experiments, or whenever accumulated dose will reach ~50 krad. If the calorimeter would be well shielded from all sides but the front side, then radiation damage would be from the front and can be relatively easy removed, since main damage would be only in the frontal 2-3 cm thick layer of the crystal.

Note, effect from the radiation damage would be different for scintillating crystals and for pure Cherenkov light generating crystals. Since main damaged part is the frontal 2-3 cm layer, for Cherenkov type crystals this does not make big difference in total amount of collected light (Cherenkov radiation is directional, and all emitted photons are dominantly in particle (forward) direction). For scintillation type crystals damage of the first few cm at the frontal side will cause significant loss of light. This is due to uniformity of scintillation radiation, the light in backward direction will be lost if no reflection.

Studies show that blue light of ~400 nm is most effective in removing the radiation damage and reset crystals attenuation length. It was estimated that the required light intensity is of an order of 1-2 mW/cm^2, thus for 2×2 cm^2 or 3×3 cm^2 crystals we need curing system with power ~5-10 mW/crystal (at λ~400-600 nm).

Two curing systems, marked "A" and "B" in the sequel, will be designed and build for the NPS calorimeter.

I. **Version "A"** is a standard curing system which uses blue light of wavelength λ~400-700 nm. The efficiency of this optical bleaching is wavelength dependent. Light of short wavelength is most effective for recovery the crystal's optical properties. But effect and actual wave length for effective curing may vary from crystal to crystal (even within the same type) .

Studies by PANDA collaboration show, that with blue light, nearly 90% of the original amplitude can be restored within first 200 minutes with photon flux of ~10^{16} photon/s. (see Fig.1).

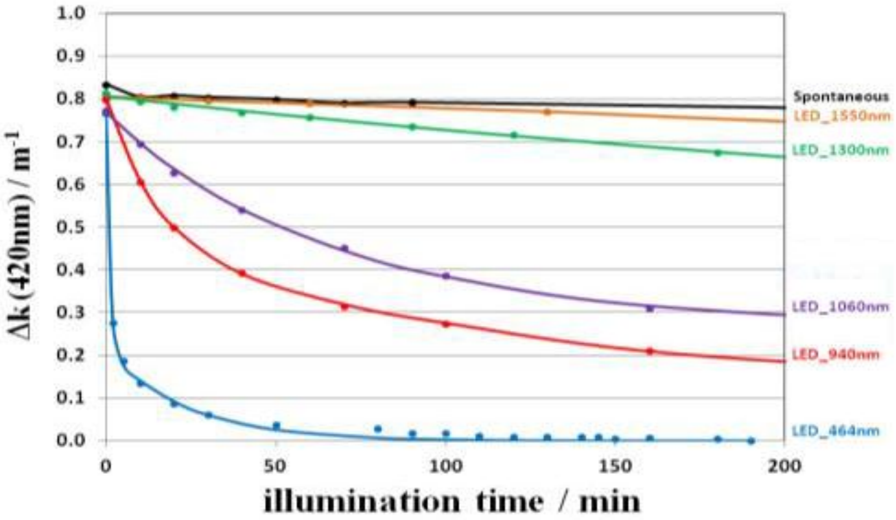


Fig.1 Recovery of 3 krad radiation induces absorption coefficient Δk at 420 nm in a $PbWO_4$ crystal by illumination with different lights. The blue light is most effective for crystal recovery. (Figure adopted from R. W. Novotny, J. Phys. Conf. Ser. 404, 2012, p012063).

Recovery strongly dependent on light intensity. Fig.2 (taken from PANDA) illustrates impact of the induced absorption coefficient when illuminating with blue light (λ=464 nm) with a photon flux of 5.8×1016 photons/s delivered by 4 identical LEDs at room temperature.

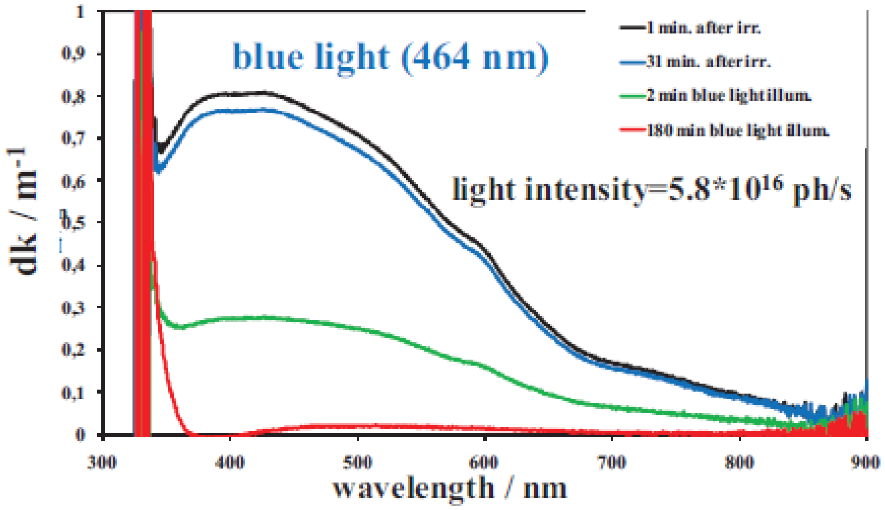
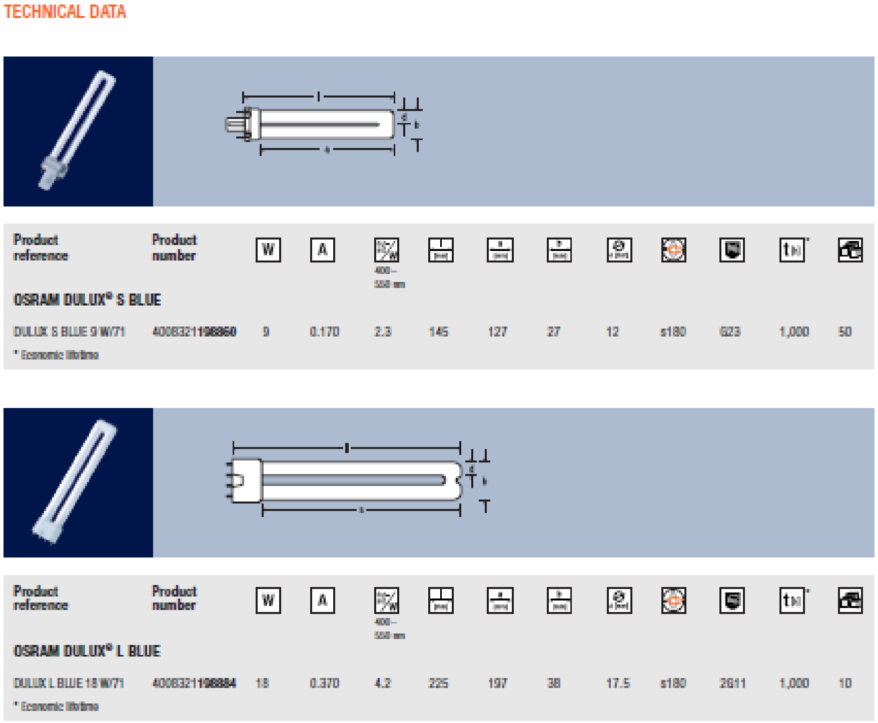


Fig.2 Recovery of 3 krad radiation induces absorption coefficient Δk when illuminating with blue light (λ= 464 nm) with a photon flux 5.8×10^{16} photons/s. (Figure adopted from PANDA collaboration, R. W. Novotny, IEEE-2009-05402124).

The NPS calorimeter curing system can be clone of the curing system of Hall C Gep-III experiment. In Gep-III with 14 W power OSRAM-DULUX UV lamps at distance ~5 cm from the TF-1 blocks they have reached recovery effect ~1.24% per 1 hour. Low power lamps and distance 2” of their system were selected because of concerns about glass heating. During the actual curing it turned out that the glass temperature rose only by few degrees, so the UV lamps could have be placed closer to the glass and be more powerful. By the way, in Gep-III no any damage of PMTs due to curing were found (after several weeks UV illumination).

The NPS calorimeter curing system will consist of high power blue lamps: 9 or 18 Watts. If curing system will be installed at ~1.0” distance from the glass then we may have ~4 or more times powerful curing system than was used in Gep. More important that these blue light lamps have wavelength (400-550 nm) which is most effective for PbWO curing (see Fig.2).
OSRAM DULUX lamps are compact fluorescent lamps with a high luminous flux. A sketch of the blue lamp and it technical data sheet taken from the company web-page are shown in Fig.3.



Product reference	Product number	W	A	400–550 nm								
OSRAM DULUX® S BLUE												
DULUX S BLUE 9 W/71	4008321198860	9	0.170	2.3	145	127	27	12	s180	G23	1,000	50

* Economic lifetime

Product reference	Product number	W	A	400–550 nm								
OSRAM DULUX® L BLUE												
DULUX L BLUE 18 W/71	4008321198884	18	0.370	4.2	225	197	38	17.5	s180	2G11	1,000	10

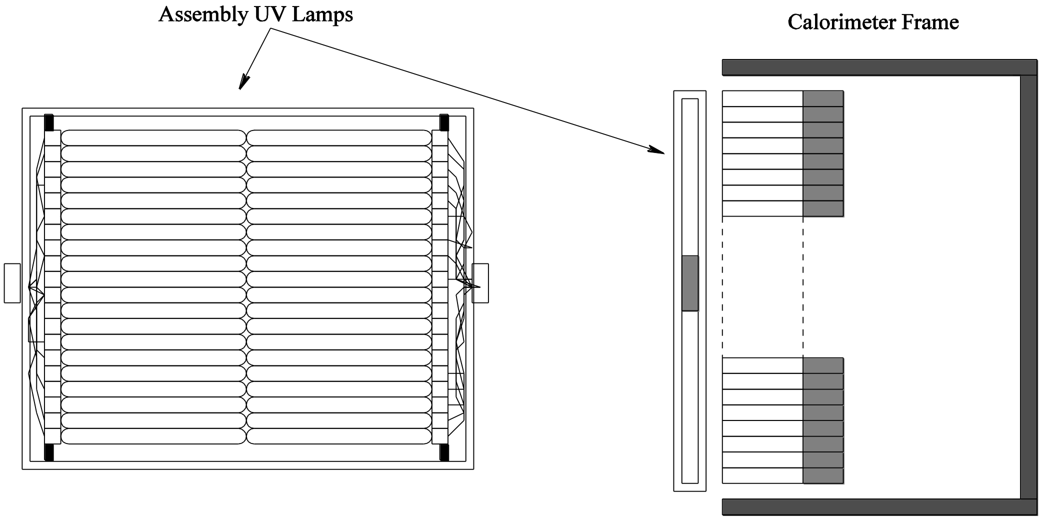
* Economic lifetime

Fig.3 OSRAM DULUX blue lamp technical data

This method of curing will require:

- Turn OFF high voltage on the calorimeter phototubes
- Hall access
- Turn OFF of the calorimeter temperature controlled system
- Dismounting and removal of the front panel of the temperature controlled box
- Installation of the frame with curing lamps

The lamps will be assembled on a frame and will cover the calorimeter hole surface when mounted at the front. From the back the lamp frame will be covered with a reflector (Al-plate covered with good quality Al-foil) for effective use of the produced light. Schematic drawing of the lamp assembly and its location during the calorimeter curing are shown in Fig.4 (a and b).



(a) (b)

Fig.4 Schematic of assembly of the lamps (a) and its position during NPS calorimeter curing (b).

The frame with curing lamps will be mounted on the front of the calorimeter and will radiate from ~6-8 hours up to ~1 day, depending on the level of radiation damage or free access time, when experimental hall is open for some other reasons (beam is down for more than ~6 hours, accelerator weekly maintenance, or energy change). The distance between lamps and calorimeter blocks must be chosen carefully to avoid non-uniform heating of the glass. The NPS monitoring system will be used to estimate effect of block recovery (by taking data before and after curing).

This method was used in experiments and works effectively for variety of crystals. In Fig.5 shown nearly full recovery of a PbF_2 crystal from radiation damage within ~10 min. of curing.

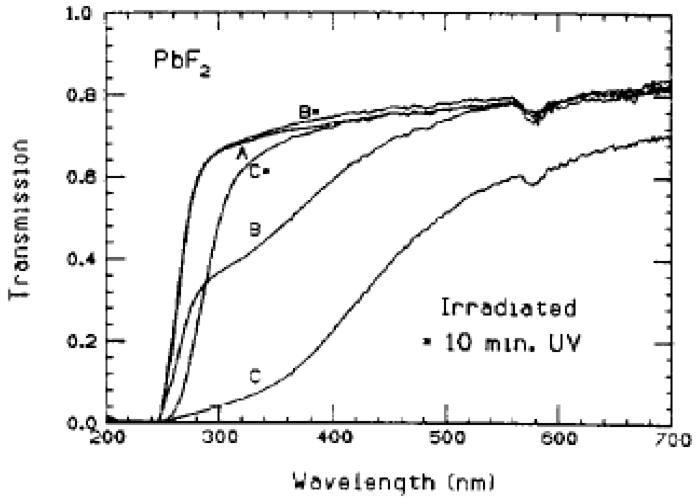
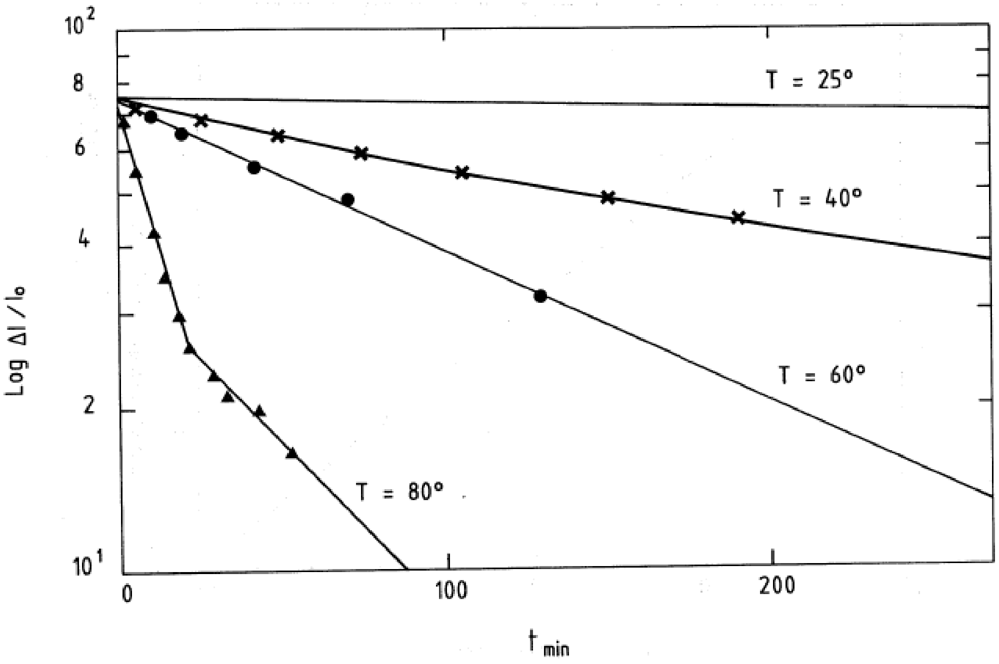


Fig. 5 Transmission of PbF_2 before irradiation (A), after 40 krad (B) radiation, after 4 Mrad radiation (C). (B*) and (C*) are same as (B) and (C) but after 10 minutes curing with UV light (365 nm) light. (Adopted from D. F. Anderson Flab-Conf-90/46, NIM A290, 1990, p.385)

Long time ago it was found that curing of damaged crystals with optical bleaching is temperature dependent, and curing is much faster when temperature is above room temperature. As an example, for the damaged BGO crystal at 80° C recovery was more than 25%, while only 4% was expected without heating. In Fig. 6 we show transmission recovery of a damaged BGO crystal (with dimension 2×2×24 cm^3) with blue light of λ=514 nm at T=25°, 40°, 60° and 80° C (figure taken from C. Laviron and P. Lecoq, CERN-EF-84-5). This mean natural rise temperature of the blocks a few degrees during curing (if this would be slowly and uniform) actually will make more effective curing process.



λ

Fig.6 Transmission recovery of a damaged BGO crystal (dimension 2×2×24 cm^3) with blue light of λ=514 nm at T=25°, 40°, 60° and 80° C. (From C. Laviron and P. Lecoq, CERN-EF-84-5).

Main Components of Curing System version "A"

- High power UV lamps (need 50 lamps OSRAM-DULUX-L blue , 9-18 Watts, proposed cost is ~20-40 \$/each, total 50×40 ≈ 2 k USD).
- Connectors for lamps (~5-7\$/each, ➔ ~0.35 k)
- Support frame design (1-2 week engineering job, ~3 k)
- Support Frame material (Al profile, 2"×2" about 6-10 m total length, ~2 k)
- Support frame fabrication (1-2 week in machine shop, ~ 3 k)
- Support frame back plate with reflector (Al plate 0.5" thickness, ~1 m × 1m, ~1 k)
- Support frame lamp protection plate (Al plate 0.5" thickness, ~1 m × 1m, ~1 k)
- Power cables for lamps (~50 m, estimated cost ~0.15 \$)

II. **Version “B”** will use visible or infra-red (IR) light for recovery. Studies show that even At longer wavelength (600-1000 nm) a significant recovery is possible but for a long time irradiation. This was tested and works very well for low doses (~3 krad) and can be operated remotely without access to the experimental area. The main difficulty of this method is low efficiency (by factor ~20-50 relative to blue light, as shown in Fig.7). This must be compensated by using high intensity (~10^{16} photons/s per block).

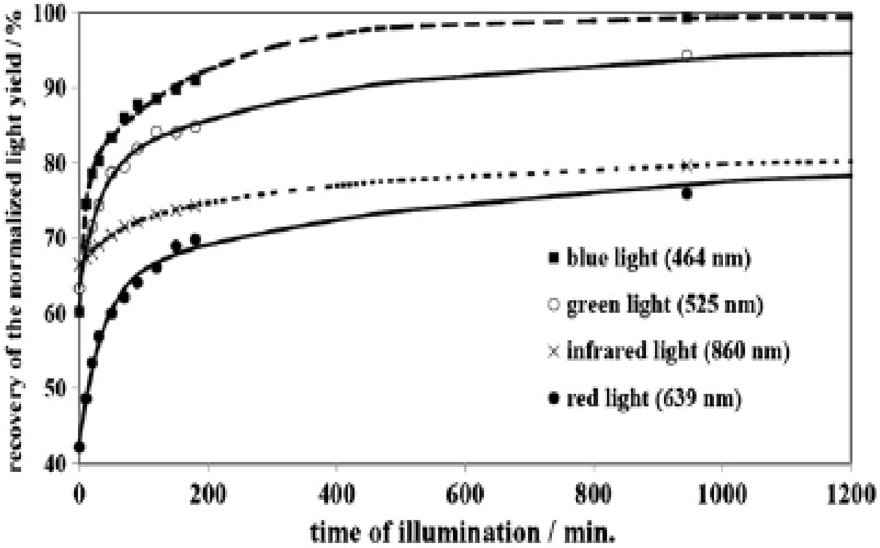


Fig.7 Infra-red recovery of the normalized light output of $PbWO_4$ crystal after 3 krad dose. (Figure adopted from V. Dormenev et al., NIM, A623, 2010, p1082).

It is very promising that such curing can be performed continuously, even without turning OFF high voltage on the PMTs, since IR light is out of quantum efficiency region of the phototubes. As an example in Fig.8 the spectral sensitivity of the Hamamatsu R7700 PMTs is shown, which was used in Hall A PbF_2 calorimeter.

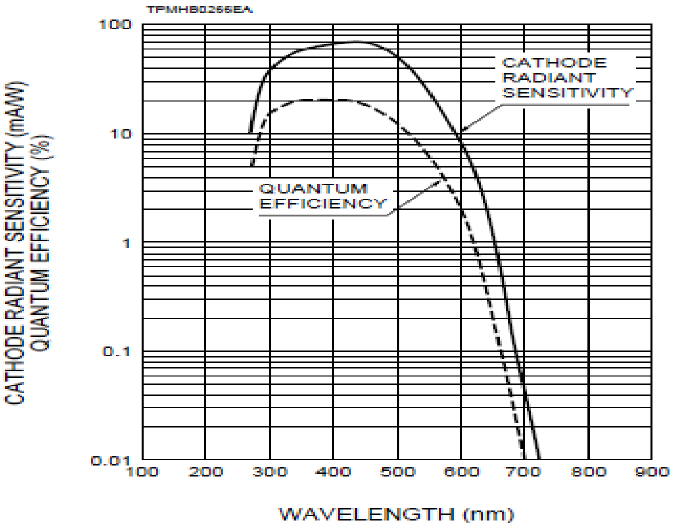


Fig.8 Spectral sensitivity range of the Hamamatsu R7700 PMT

Note, curing can be used with PMT high voltage ON if its emission spectrum does not contain any fraction of light below 700 nm !

Illuminating crystals with infrared light (λ≈940-1040) in curse of the experiment may keep its transmittance at good enough level due to continuous curing. Based on studies performed by PANDA group we may assume that at dose rates ~1 krad/h with a IR light of λ~940 nm and intensity ~2×10^{17} one may continuously recover degradation of the crystal.
Fig. 9 illustrates significant improvement of the optical transparency of damaged crystal (after 3 krad dose) when illuminating with the IR light λ=940 nm (left) and λ=1060 nm (right) observed by PANDA group.

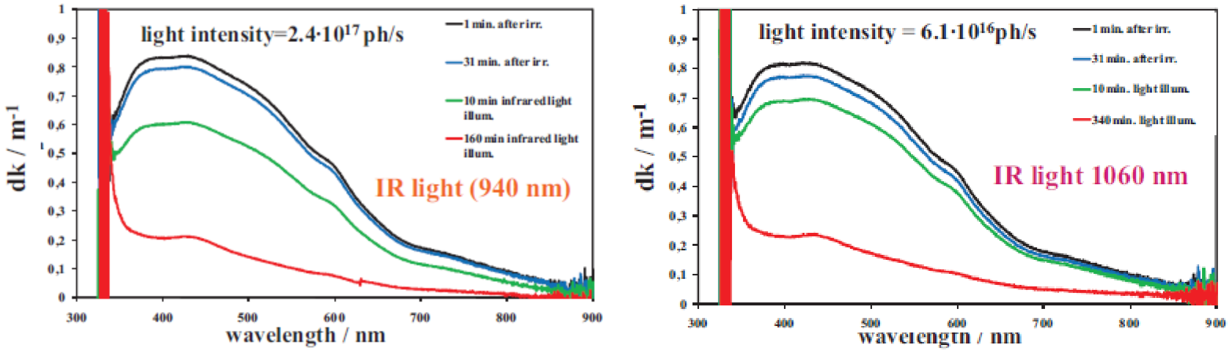


Fig.9 Change of the spectral distribution of the induced absorption coefficient dk after accumulated γ-ray dose 3 krad due to recovery stimulated with infrared light of λ=940 nm (left) and λ=1060 nm (right) . (From PANDA collaboration, R. W. Novotny, IEEE-2009-05402124).

For curing version "B" we may consider two approaches: permanent IR illumination from the frontal side of the calorimeter when curing light system will be mounted inside the calorimeter box (B-1), or light source is out from the calorimeter box and IR light is transported to blocks by means of optical fibers from the back or front of the crystals (B-2).

B-1: In this case we may use system similar to version "A" but using permanent installed IR light source, such as LED. A set of infra-red LEDs can be assembled on special board, with LEDs at distance ~1.5 cm from each other, covering surface of ~80×80 cm^2. The board with about ~2000 LEDs will be mounted on plastic or Al plate and will be installed permanently at the front of the blocks. Note, all the assembly shall fit inside the calorimeter box and be easily assembled or taken out if needed. In this case calorimeter box shall have an additional socket for electrical powering of the LED system. Fig.10 show schematic drawing of the assembly of LEDs (a) and its position relative to the calorimeter blocks (b).

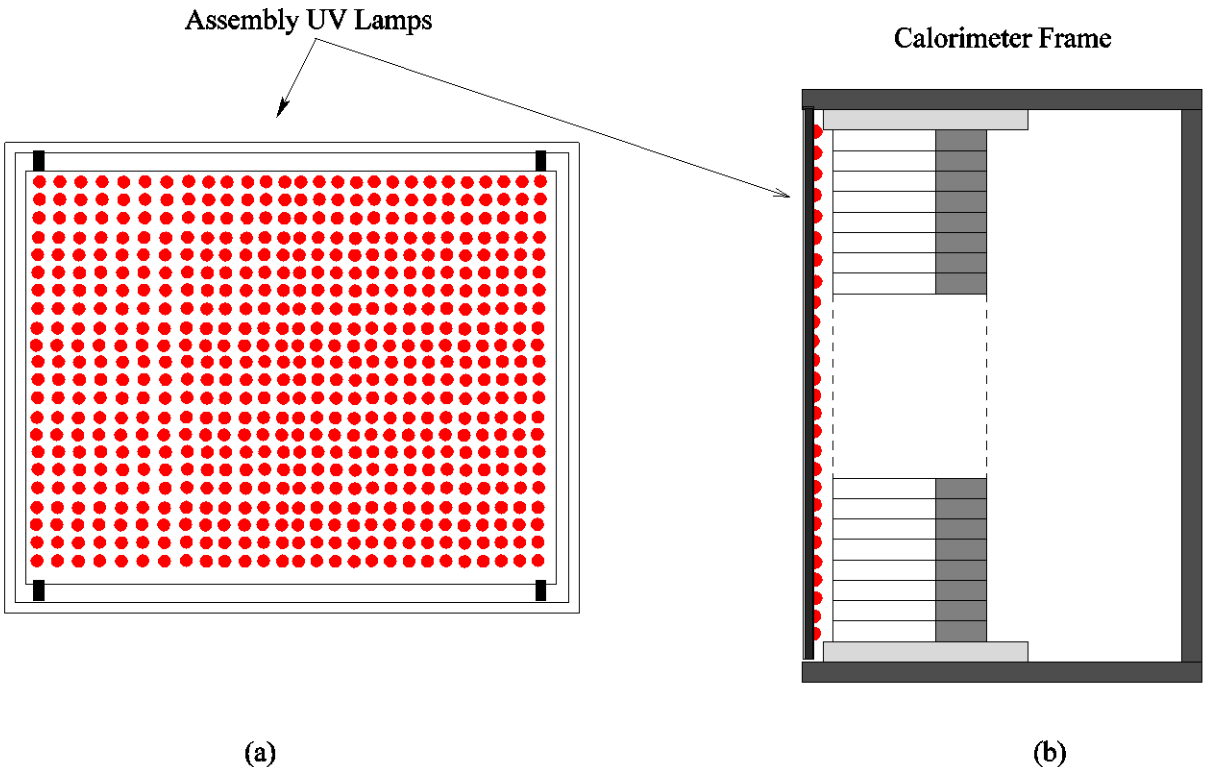


Fig.10 Schematic drawing of assembly of LEDs (a) and its position relative to blocks (b).

For effective curing the IR light system must be capable to provide intensity from ~5×10^{16} to ~3×10^{17} photons/s pet block, since the curing time will strongly depends on it (see Fig.11).

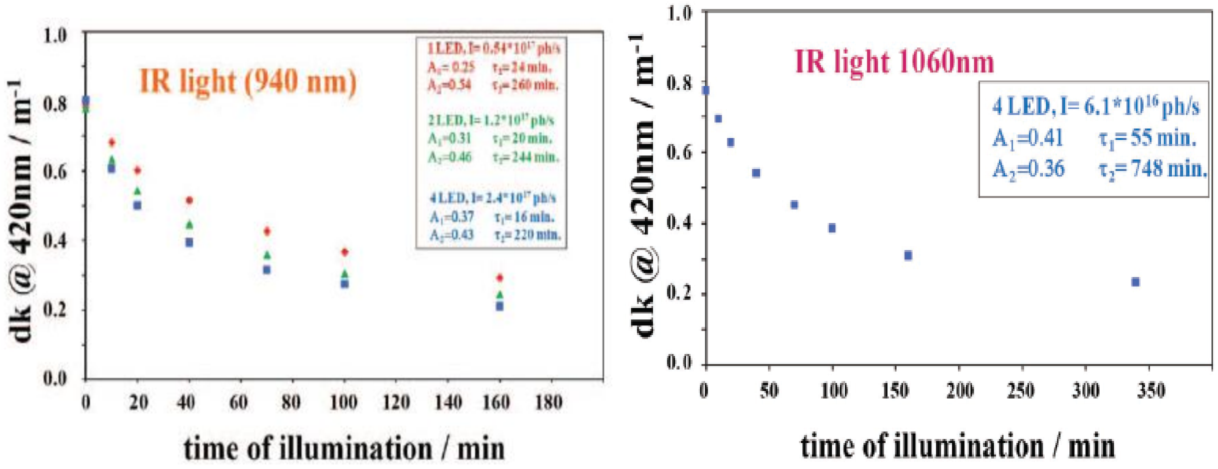


Fig.11 Left: Change of the induced absorption coefficient dk at λ=420 nm after dose 3 krad due to recovery simulated with IR light of 940 nm. The measurement was performed at room temperature with infrared light by using 1, 2 or 4 LEDs as light sources. Right: Same as Left figure but for IR light of 1060 nm. (Adopted from R. W. Novotny, IEEE-2009-05402124).

Main Components of Curing System version”B-1” are:

- High power infra-red LEDs (~1500-2000, estimated cost ~3 k). IR light emitted diodes with power in the range of 0.5-5 W can be found in product-list of Hamamatsu, LSE INC, HERO-LED and other companies)
- Support frame design (1-2 week engineering job, ~2 k)
- Support frame material (~0.25-0.5” thickness Al sheet, size 1 m × 1 m, ~0.5 k)
- Support frame construction, assembling of the LED system (~2 month, ~ 5 k)
- Develop, mount and test of the Pulsar system for ~2000 LEDs (estimated cost ~1-2 k). This could be modified for ~1000 LED version of similar circuit developed by JLab electronic group for PbF2 calorimeter, or simplified version of similar electronics developed for Hall D.
- Low voltage (5-10 V) power supply, wire for pulsar-LED connections (~2 k)

Radiated heat of full assembly of LEDs, their power and amount must be adjusted with capability of the calorimeter temperature controlled frame. It is also important to select LEDs which can withstand ~10 Mrad or more radiation doses without significant degradations (radiation hard LED). This strongly depends on the material which is used for LED production. From the type of material also depends the emitted light color (see Table).

	Wavelength (nm)	**Color Name**	**LED Dye Material**
⬛	940	Infrared	GaAIAs/GaAs -- Gallium Aluminum Arsenide/Gallium Arsenide
⬛	880	Infrared	GaAIAs/GaAs -- Gallium Aluminum Arsenide/Gallium Arsenide
⬜	850	Infrared	GaAIAs/GaAs -- Gallium Aluminum Arsenide/Gallium Arsenide
🟥	660	Ultra Red	GaAIAs/GaAs -- Gallium Aluminum Arsenide/Gallium Arsenide
🟥	635	High Eff. Red	GaAsP/GaP - Gallium Arsenic Phosphide / Gallium Phosphide
🟥	633	Super Red	InGaAIP - Indium Gallium Aluminum Phosphide
🟧	620	Super Orange	InGaAIP - Indium Gallium Aluminum Phosphide
🟧	612	Super Orange	InGaAIP - Indium Gallium Aluminum Phosphide
🟧	605	Orange	GaAsP/GaP - Gallium Arsenic Phosphide / Gallium Phosphide
🟨	595	Super Yellow	InGaAIP - Indium Gallium Aluminum Phosphide
🟨	592	Super Pure Yellow	InGaAIP - Indium Gallium Aluminum Phosphide
🟨	585	Yellow	GaAsP/GaP - Gallium Arsenic Phosphide / Gallium Phosphide
🟩	574	Super Lime Yellow	InGaAIP - Indium Gallium Aluminum Phosphide
🟩	570	Super Lime Green	InGaAIP - Indium Gallium Aluminum Phosphide
🟩	565	High Efficiency Green	GaP/GaP - Gallium Phosphide/Gallium Phosphide
🟩	560	Super Pure Green	InGaAIP - Indium Gallium Aluminum Phosphide
🟩	555	Pure Green	GaP/GaP - Gallium Phosphide/ Gallium Phosphide
🟦	525	Aqua Green	SiC/GaN - Silicon Carbide / Gallium Nitride
🟦	505	Blue Green	SiC/GaN - Silicon Carbide / Gallium Nitride
🟦	470	Super Blue	SiC/GaN - Silicon Carbide / Gallium Nitride
🟪	430	Ultra Blue	SiC/GaN - Silicon Carbide / Gallium Nitride

Best radiation hardness show LED based on SiC, GaN and AlGaInP.
Since, this method still in development stage we need build a prototype with effective area ~10×10 cm^2 and test it with PbWO or PbF$_2$ crystals (matrix 3×3) before we finalize the best configuration, type and power of LEDs and design of the real curing system

B-2: This option for permanent IR curing can use powerful light source outside from the calorimeter box and delivery light to the each individual block by fiber (as we are doing for monitoring).

The primary light source could be 200-300 W xenon or mercury lamp with a mono-chromic or di-chromic selection of the IR light, or with wavelength shifter. It also can be set of 1-2 lasers with a WLS or with di-chromic selector. As in the case of monitoring, primary light (with selected wave length) must be split into many channels (assuming ~1000) and delivered to each individual block by silica or quartz fibers (for high intensity better use fibers with core diameter 0.6-1.0 mm). Similar system have been tested, back in 1995, for the IR curing in situ of crystals BaF2 (see Fig.12).

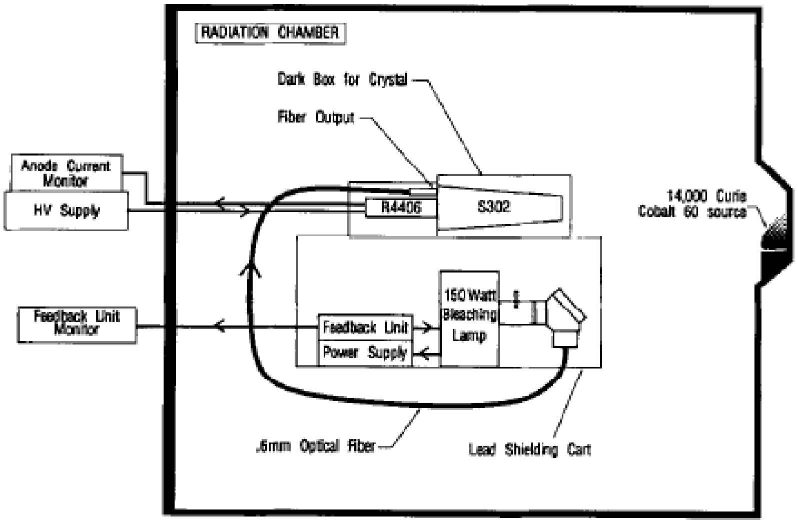


Fig.12 Setup for in situ bleaching of BaF2 crystal, using a 150 W xenon (or 200 W mercury) lamp and 0.6 mm diameter fiber. (Adopted from D. A. Mao et al., NIM A 356, 1995, p309)

Here again we need some prototyping and studies. Need find out how connect optical fibers to individual crystal from the back near the PMT in order to deliver light pulses from the IR source. Fiber with diameter 0.6 mm makes this more complicated than in case of monitoring (where we are using 200 µm fibers). In this case, best solution would be combine monitoring and curing systems and use same fiber for both purposes. (Need to resolve many unknown problems!).

We may also attach curing IR fibers from the frontal side of the blocks, and use supports for fiber similar what was used in CMS (shown in Fig.13).

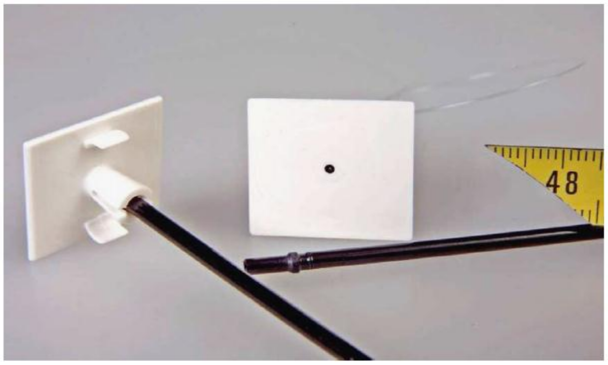


Fig.13 A CMS barrel ferrule support, showing the fiber ferrule snapped in place. (Figure adopted from M. Anfreville et al., NIM A 594, 2008, p292).

We amy use only fibers, glue, optical grease, electronic components and anyother material, which can withstand ~10 Mrad or more radiation doses, specifically when they are planning to be used in the frontal side of the calorimeter.

Main Components of Curing System version "B-2" are:

- ~300 W power xenon or mercury lamp, or 1 mJ/pulse laser (Oriel or Newport, cost 15 k))
- Monochromic or dichromic selector for 400-1000 nm light (~5 k)
- Optical fiber splitters (as in case of monitoring but for 0.6 mm fibers)
- Optical fibers with core diameter 1mm and 0.6 mm
- Fiber support structures (for ~1200 block-fiber connection, estimated price ~ 0.5-1.0 k)

Note, both B-1 and B-2 methods with IR curing in situ still in development stage. We need to test with PbWO or/and PbF_2 crystals, optimize source, check curing efficiency, time before we will finalize best configuration.

Conclusion:

- **Probably we can go with version A !**
- **Need prototyping and tests for version "B"**