The NPS Calorimeter Light Monitoring and Curing Systems
(and proposed prototype studies)

H. Mkrtchyan, T. Horn, R. Ent, A. Mkrtchyan, V. Tadevosyan

(For NPS Collaboration)

Hall C Collaboration Meeting, Jlab, 21-22 February, 2014

NPS Science Motivation

A Neutral Particle Spectrometer (NPS) is required to carry out the JLab 12 GeV Hall C program of precision cross section measurements and L/T separations, extending the charged-particle (p, $\pi^{+/-}$, $K^{+/-}$) measurements to neutral particles (γ and π^0). It will open new opportunities in Hall C, utilizing the well-understood HMS and the new SHMS infrastructure.

Proposals benefitting from the NPS facility, so far:

- E12-13-007, Measurement of Semi-Inclusive π^0 Production as Validation of Factorization. (25 days approved, A- rating, running concurrent with E12-13-010).

- E12-13-010, Exclusive Deeply Virtual Compton and Neutral Pion Cross-Section Measurements in Hall C. (53 days approved, A rating).

    - PR12-13-009, Wide-angle Compton scattering at 8 and 10 GeV photon energies. (Deferred by PAC40).

    - LOI12-13-003 – Large Center-of-Mass Angle, Exclusive Photoproduction of π^0 Mesons at Photon Energies of 5-11 GeV.

Plan to propose PR12-13-009 and LOI12-13-003 as one combined experiment to PAC42 – see separate presentation

NPS Facility

- a ~25 msr neutral particle detector consisting of 1116 PbWO4 crystals in a temperature-controlled frame – using PRIMEx crystals or more likely new.

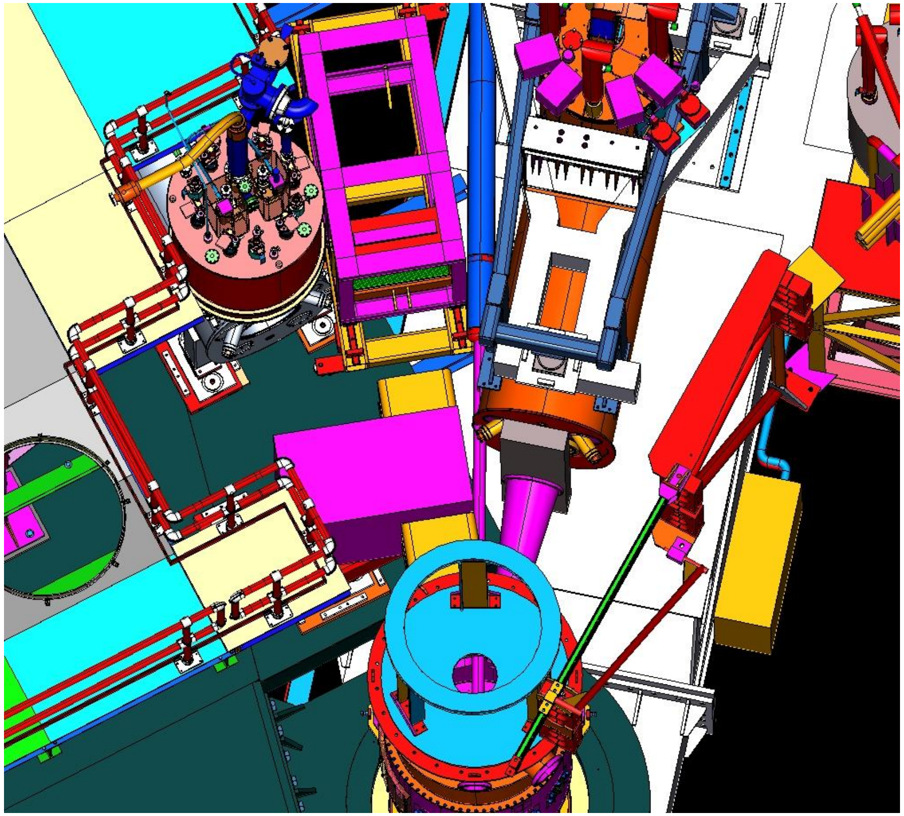
- HV distribution bases with built-in amplifiers for operation in a high-rate environment – new

- Essentially deadtime-less digitizing electronics to independently sample the entire pulse form for each crystal – JLab-developed Flash ADCs

- Two new sweeping magnets, one horizontal bending with ~0.3 Tm field strength, and one vertical bending with ~0.6 Tm field strength for larger angles/WACS. Both designed to use an existing power supply.

- Cantelevered platforms off the SHMS carriage to allow for remote rotation (in the small angle range), and platforms to be on the SHMS carriage (in the large angle range) – new

- A beam pipe with as large critical angle as possible to reduce beamline-associated backgrounds – further study showed only a small section needs modification (JLab/Hall C)

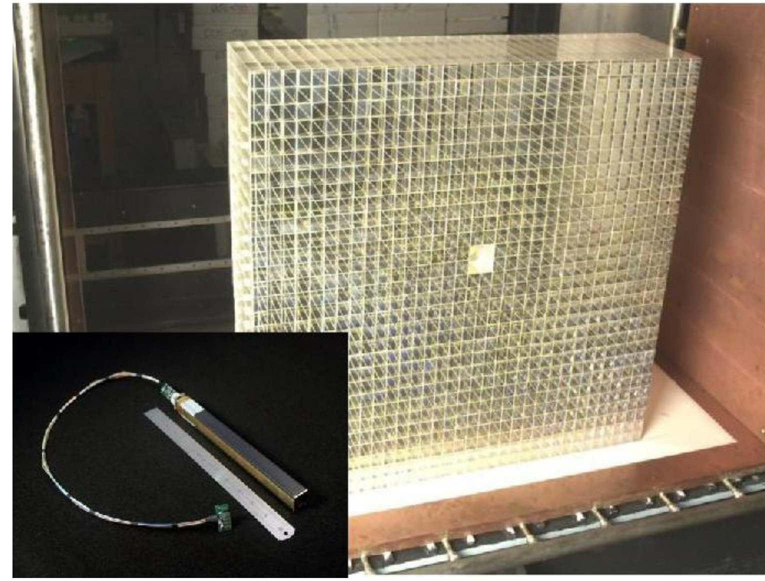


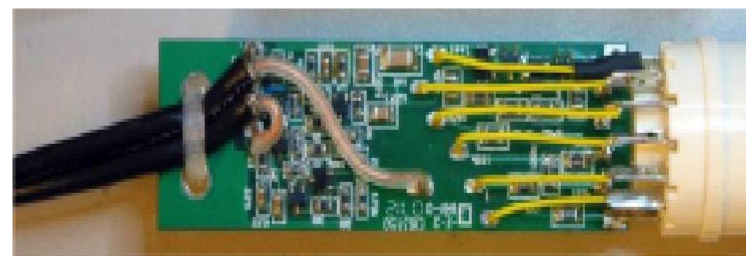
HV and cabling is assumed from JLab, and similar as for BigCal

NPS Detector

Original concept:
Assume use of PbWO4 crystals of PrimEx, with new active divider design

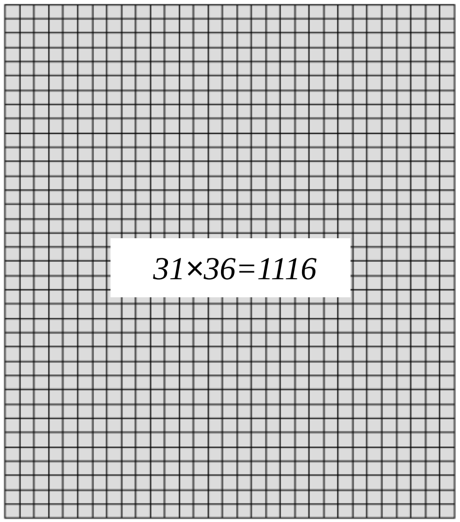
New concept:
To alleviate scheduling issues, **also** consider a potential mix of PbWO4 and PbF2





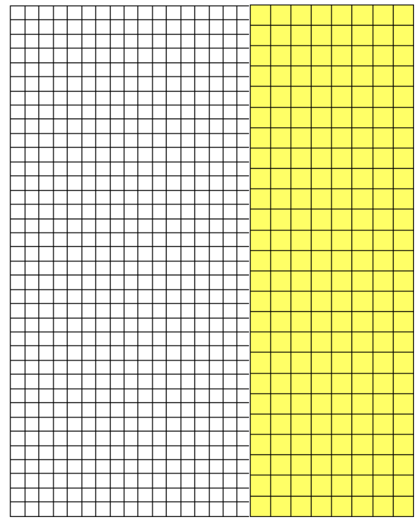
Possible options for the NPS calorimeter

64×74 cm²



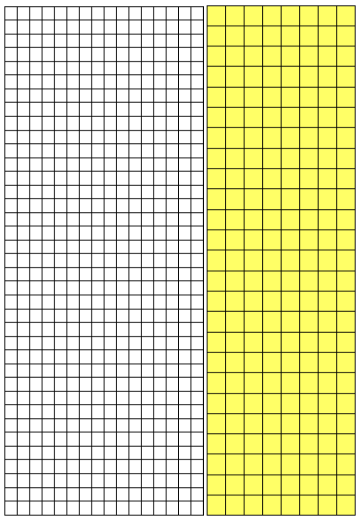
All block are $PbWO_4$

59×75 cm²



612 $PbWO_4$ + *200* PbF_2

57×75 cm²



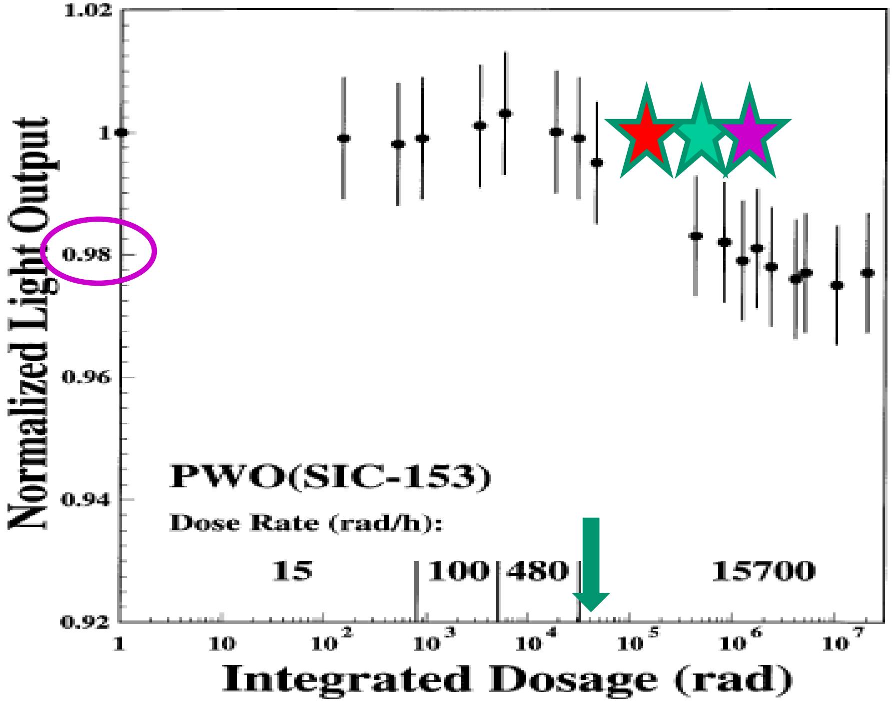
592 $PbWO_4$ + *200* PbF_2

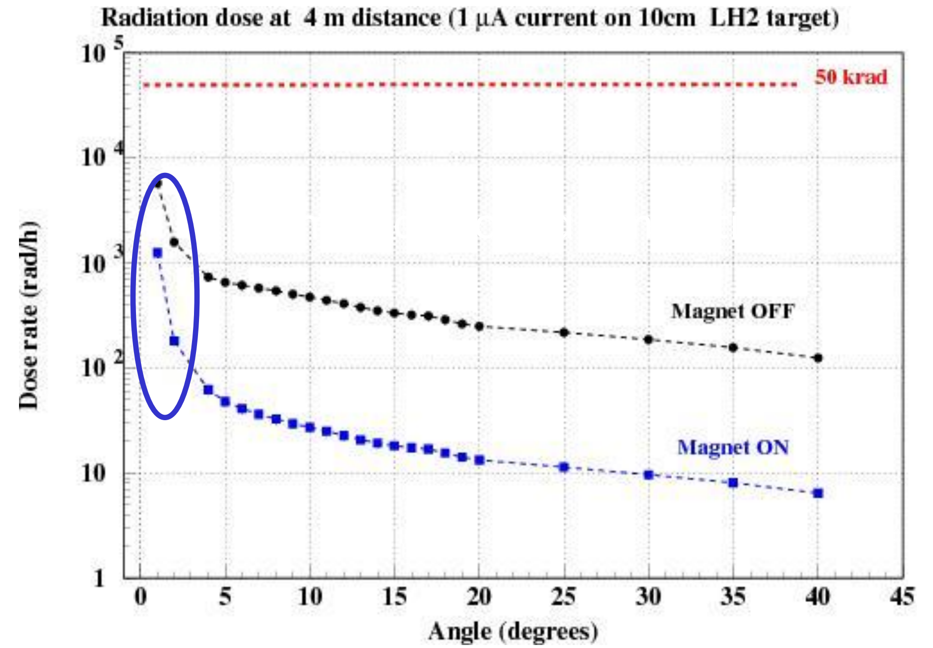
$PbWO_4$ blocks dimensions: 2.05×2.05 cm²

PbF_2 blocks dimensions: 3.0×3.0 cm²

Final geometry of the calorimeter will be selected based on availability of the blocks and results of MC studies.

Levels of radiation damage





LHC radiation dose studies: Conservative dose limit = 50-few 100 krad

If energy resolution is not a big issue: doses of 1-few Mrad also fine

Background simulations: Dose dominated by small-angle operation

- PR12-13-007: integrated dose < 500 krad
- PR12-13-009: integrated dose = 150 krad
  (corresponds nicely with scaling from Hall A/RCS experiment)
- PR12-13-010: integrated dose = 1.7 (3.4) Mrad in center (edge)

Radiation Damage and Curing

PbWO4 spontaneously recovers from ~ 1 Mrad damage in ~30 days at ambient conditions. A fast and effective way of in-situ curing is optical bleaching. ***We are still studying the best method for our experiments***.

A) Standard curing at 500-700 nm wavelengths

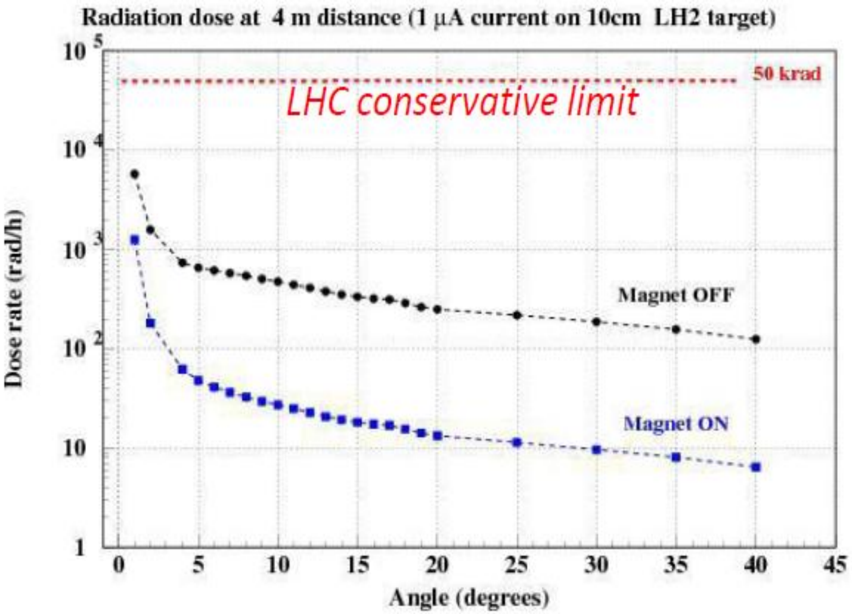
- **Requires hall access**, removing front panel and installing the curing system
- **2 shifts needed** (recovery time ~10-15 hours)
- may be done opportunistically during accelerator configuration changes or (extended) beam studies

B) Stimulated recovery with visible and IR light

- In development stage: **J. of Phys.: Conf. Ser. 404 (2012) 012063**.
- Proven to work for shallow doses (~30 Gy)
- **Can be operated remotely, no hall access needed**
- Light intensity ~10^{16} photon/s per block, can be supplied by a set of LEDs
- Fast curing with blue light, with PMTs off
- Continuous curing with IR, with PMTs on
- Further feasibility studies needed

Radiation conditions in Hall C

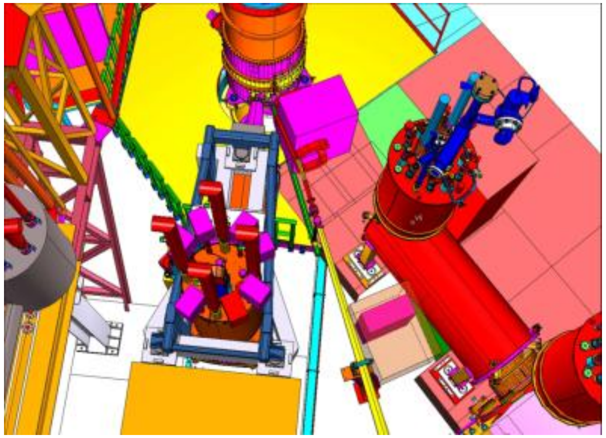
The damage to crystals is a limiting factor for beam current !

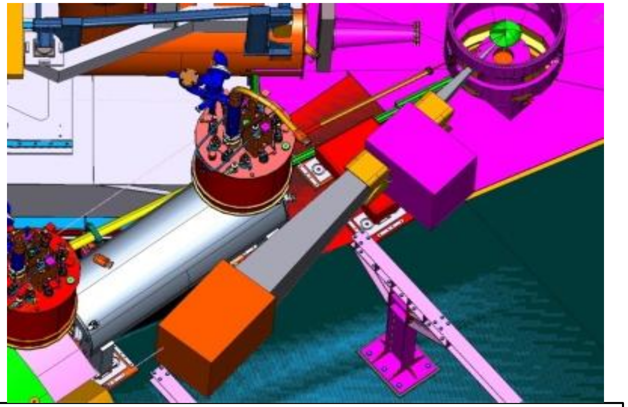


Expected dose rate versus angle

(Based on P. Degtiarenko's simulations.)

- **The radiation background is strongly angular (and energy) dependent.**
- **The magnet will sweep off most of the charged background below 300 MeV.**
- **Remaining low energy photon flux is capable to damage crystals (darkening, mostly in the first few cm).**





- **The detector will be operated in open geometry, prone to radiation damage.**
- **Curing of the crystals needed once per 2-3 weeks (after ~50 krad dose accumulation at rates <100-150 rad/h).**

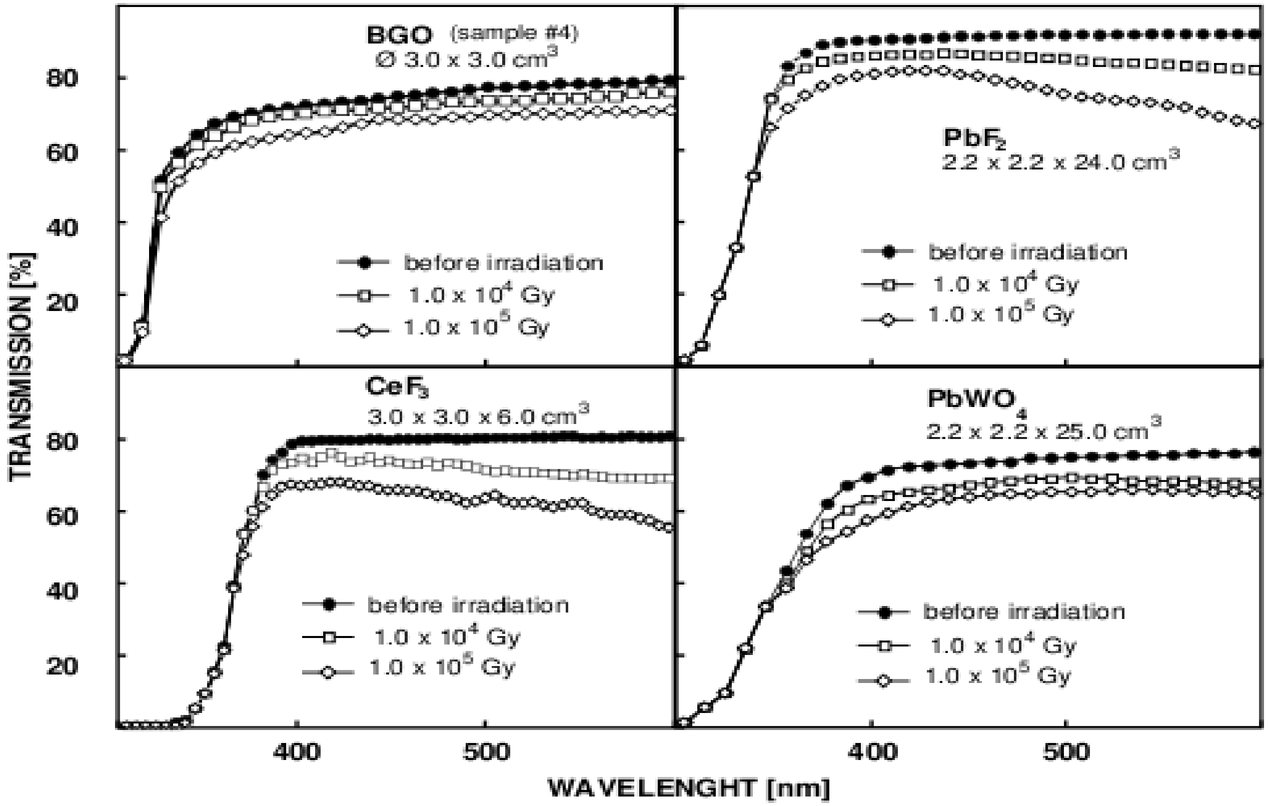
NPS Calorimeter Required

For good and stable performance in a curse of the long and high luminosity experiments the NPS calorimeter requires:

- Temperature controlled frame to minimize the crystal light-yield variation
- Light monitoring system for calibration & quality control of the crystals & PMTs
- Stimulated curing system for recovery of radiation caused damage of the crystals

Radiation damage of heavy crystals

(From R. Y. Zhu et al., CMS TN/95-157)

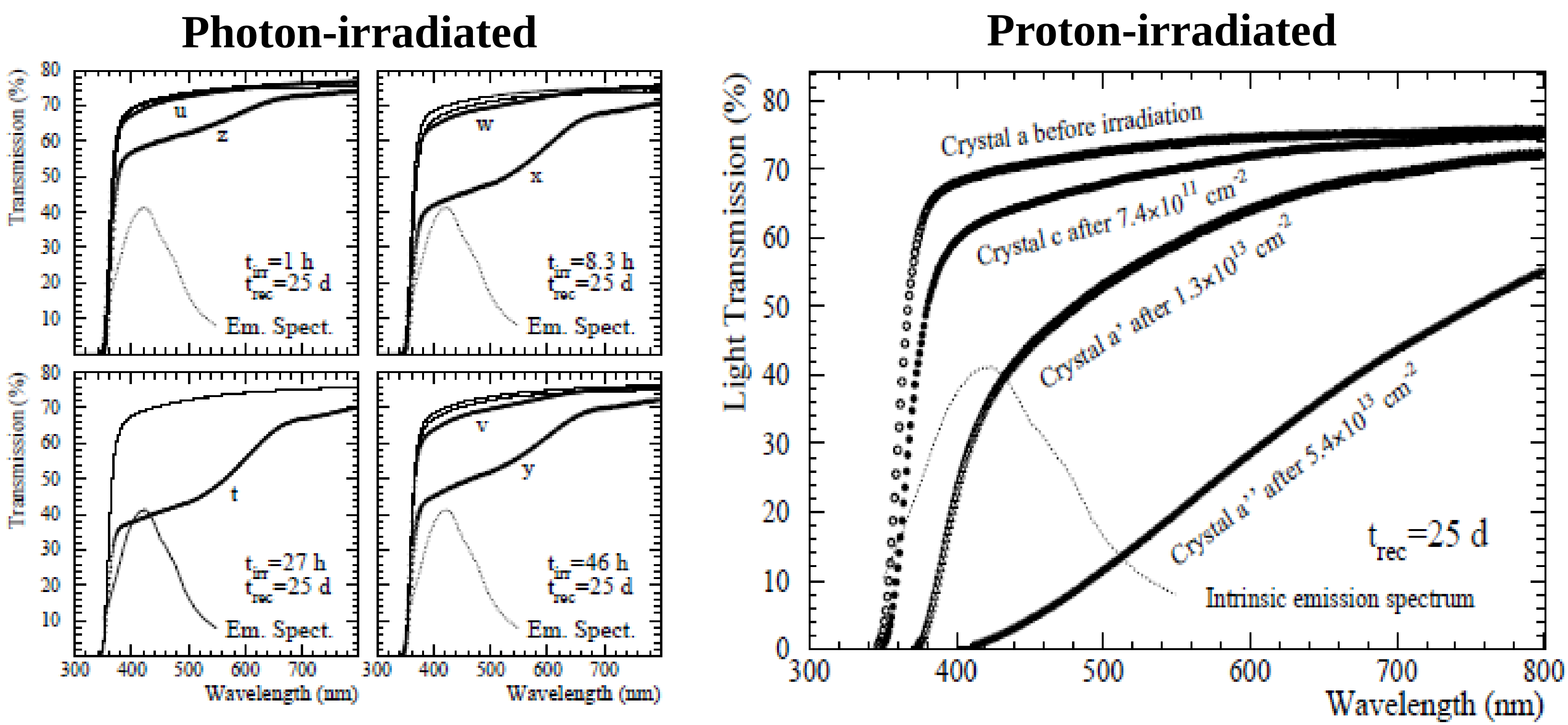


1 Gy = 100 rad

Effect of 1-10 Mrad accumulated dose on crystal transmission.

- Modest damage for nearly all crystals occurs at doses above ~10-20 krad.
- For integrated doses of 1-2 Mrad the radiation damage is significant.
- Radiation damage of the $PbWO_4$ and PbF_2 at doses below ~1 Mrad similar.

Photon & Proton induced damage in $PbWO_4$

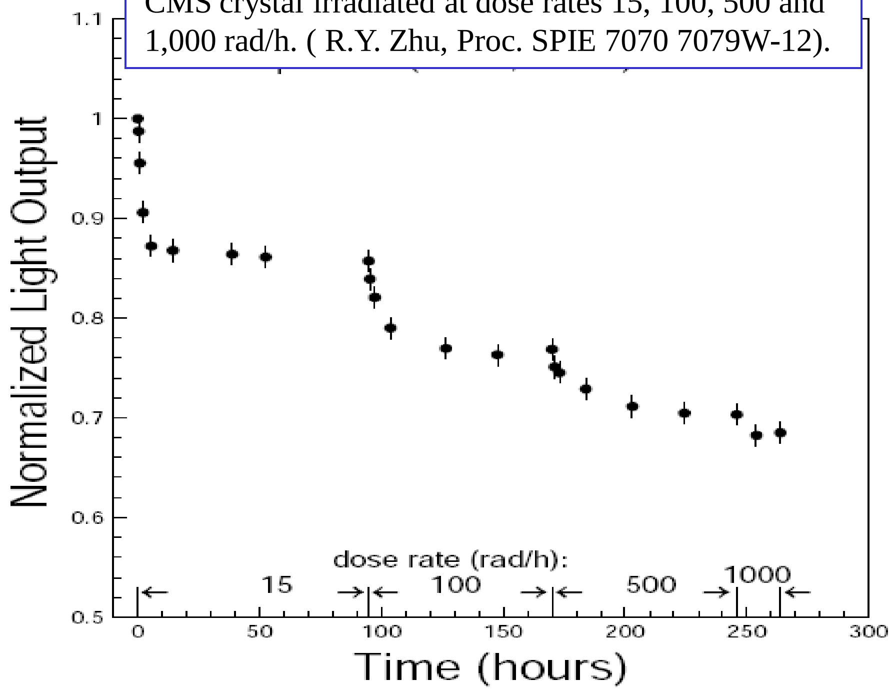


(From M. Huhtinen et al., ETHZ-IPP-PR-2004-03, Swiss Institute for Particle Physics)

- Degradation of the crystal optical properties depends on radiation dose rate, accumulated dose, and type of the background radiation particles.
- **A clear differences in the Transmission damage induced by protons relative to the γ.**
- **In proton-irradiated crystals, the band-edge shifts towards longer wavelengths region, while band-edge remains stable in the γ-irradiated crystals.**

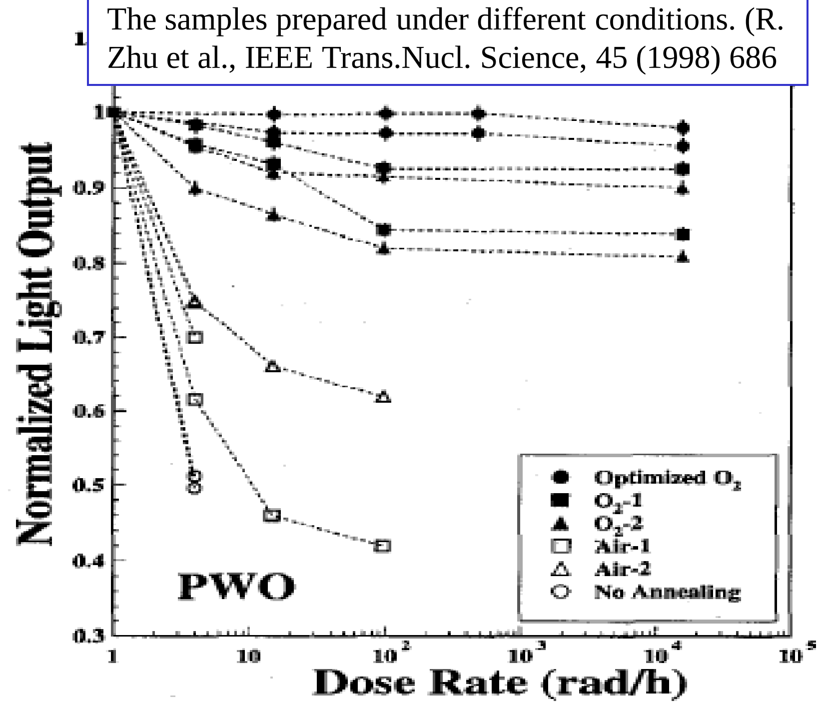
γ-ray induced radiation damage in $PbWO_4$ crystals

CMS crystal irradiated at dose rates 15, 100, 500 and 1,000 rad/h. (R.Y. Zhu, Proc. SPIE 7070 7079W-12).



Normalized LO of $PbWO_4$ as a function of time under irradiation

The samples prepared under different conditions. (R. Zhu et al., IEEE Trans.Nucl. Science, 45 (1998) 686



The normalized light output versus the dose rate

- The photon induced damage at given dose rate saturates after a few hours of exposure.
- The degradation of the light output shows a clear dose rate dependence.
- Degradation of the crystals under radiation may vary from sample to sample.
- Its depends on composition of the crystals and conditions of their preparation.
- Studies show that the scintillation mechanism in $PbWO_4$ is not affected by radiation.
- The loss of light output is due to absorption caused by radiation, and it is curable.

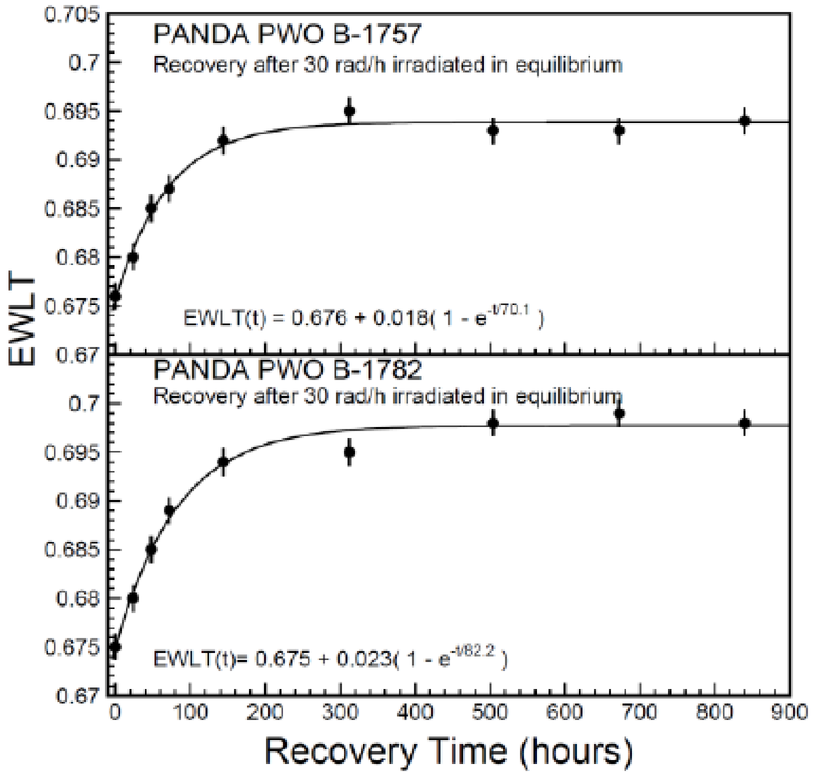
Spontaneous recovery of the crystals radiation damage

After irradiation, a spontaneous recovery of the transmittance and light yield at room temperature has been observed for $PbWO_4$ and PbF_2, and other crystals.

(R.-Y. Zhu, J. Phys.Conf. Ser. 404, 2012, p.012025)

Emission weighted longitudinal transmittance (EWLT)

$$EWLT = \frac{\int LT(\lambda)Em(\lambda)d\lambda}{\int Em(\lambda)d\lambda}$$

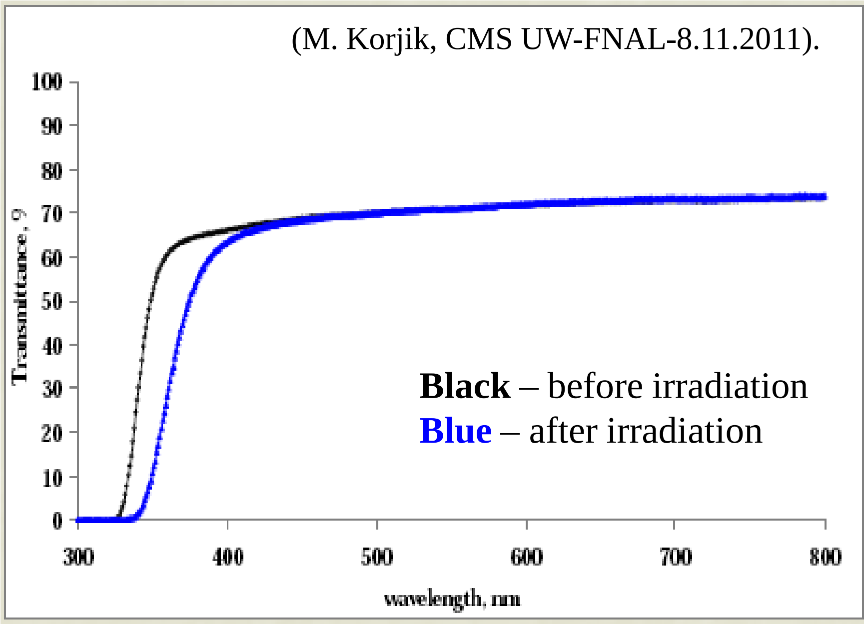


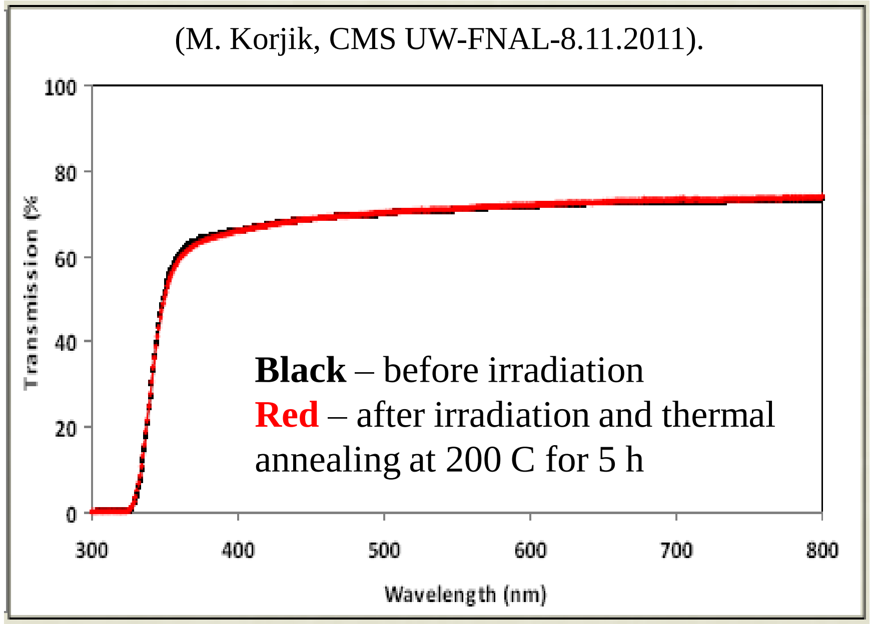
Recovery of the $PbWO_4$ emission weighted longitudinal transmittance

- **Crystals will spontaneously recovered their transmission but it will take very long time.**
- Recovery of the $PbWO_4$ transmittance irradiated at 30 rad/h in equilibrium will take ~20 days.
- PbF_2 crystals irradiated with a dose of ~10 krad a recovery of 10-15% was reached after 4 days

Thermal recovery radiation damage of $PbWO_4$

Radiation damage of $PbWO_4$ crystals by protons (integral fluence 3×10^{13} p/cm^2).





- **Full recovery of p-induced damage can be achieved by annealing at 200 ℃.**
- **Thermal annealing is very effective but it can not be performed in situ and will require full disassembling of the calorimeter.**
- **More practical and effective way of $PbWO_4$ *in-situ* curing is <u>optical bleaching</u>.**

Simulated recovery radiation damage of $PbWO_4$

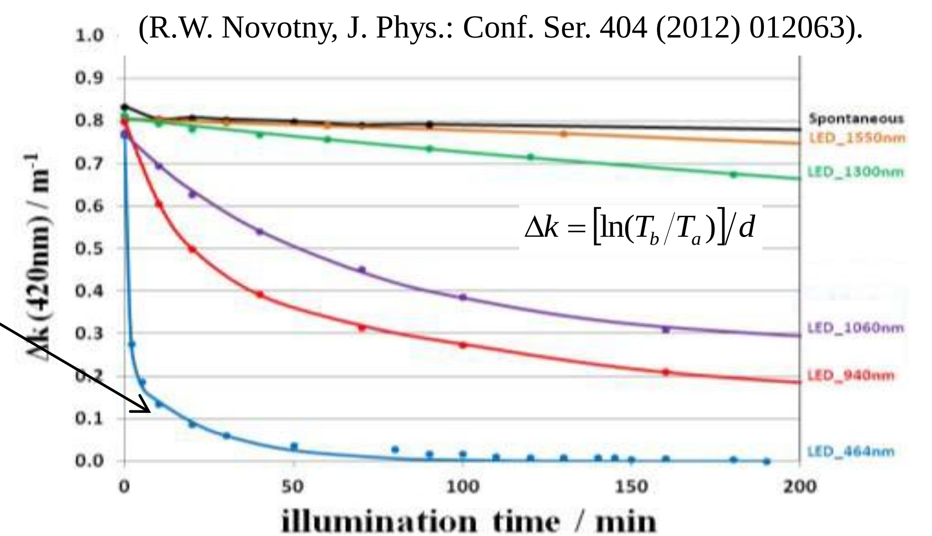
Effective way of $PbWO_4$ *in-situ* curing is optical bleaching.

Two approaches we are considering:

A) Standard curing at light λ~400-600 nm

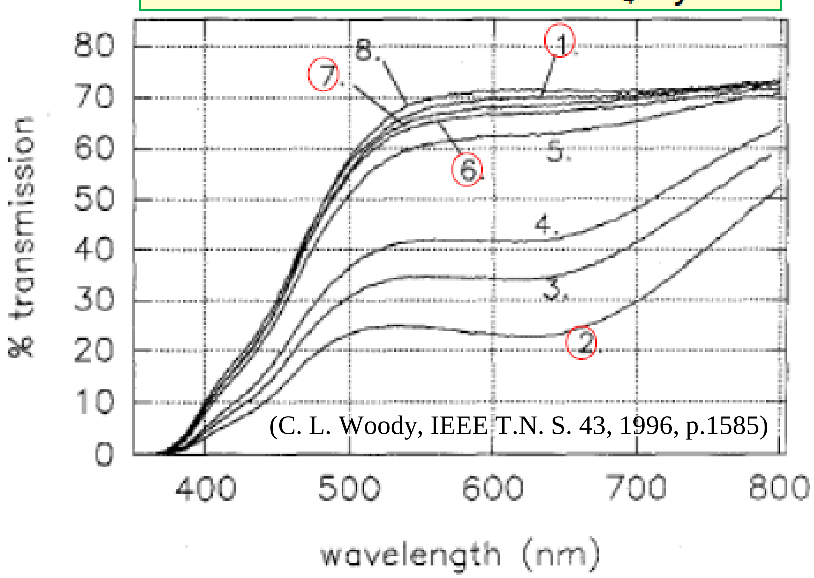
- Requires PMTs off and hall access, removing front panel & installing the curing system
- Curing strongly depends on the light wavelength, thus fast curing can be done with blue light
- With blue light nearly 90% of the original signal can be restored within first 200 minutes with photon flux of $\sim 10^{16}\ \gamma/s$

(R.W. Novotny, J. Phys.: Conf. Ser. 404 (2012) 012063).



Recovery of 3 krad radiation induced absorption coefficient Δk at 420 nm in a PbWO, by illumination with different lights.

Transmission of 21cm $PbWO_4$ crystal



(C. L. Woody, IEEE T.N. S. 43, 1996, p.1585)

(1)- before radiation,
(2)- after a dose of 834 krad,
(3)- after 5 h of bleaching at 700 nm,
(4)- after 12 h at 700 nm,
(5)- after 5 h at 600 nm (5),
(6)- after 10 h at 600 nm,
(7)- after 7 h at 640 nm,
(8)- after 2 h of annealing (200 °C).

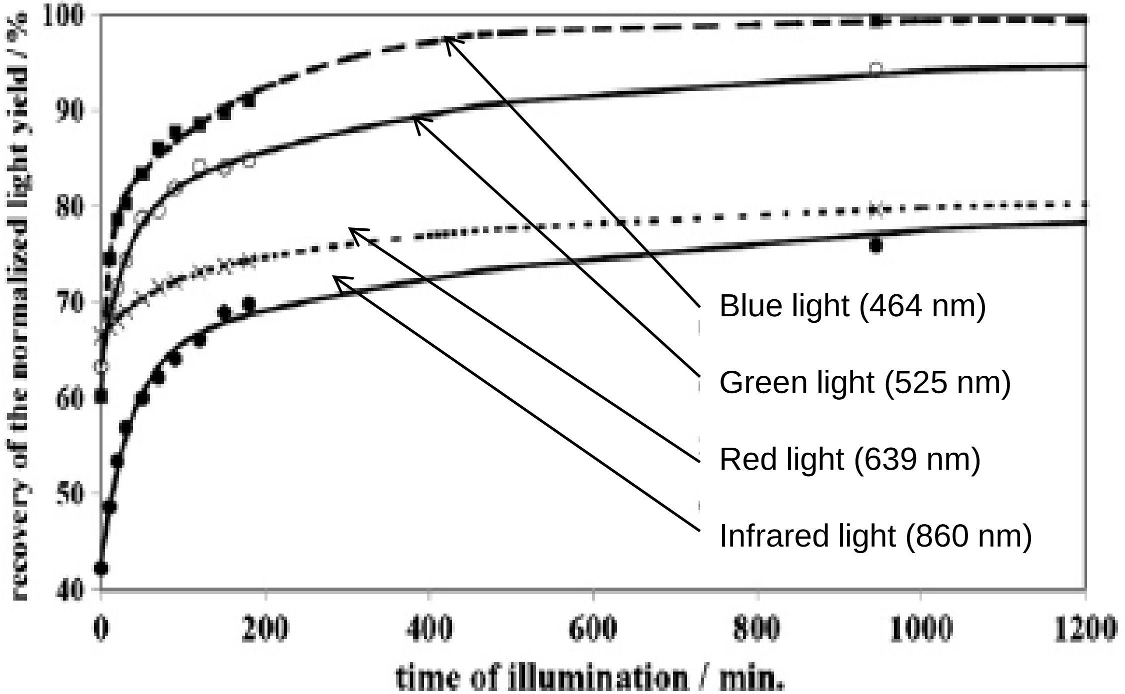
Simulated recovery of the $PbWO_4$ with IR light

B) Recovery with IR light λ~800-1000 nm

▪Works very well for low doses (~3 krad)

▪Can be operated remotely, no hall access

(V. Dormenev et al., NIM A623, 2010, p1082)

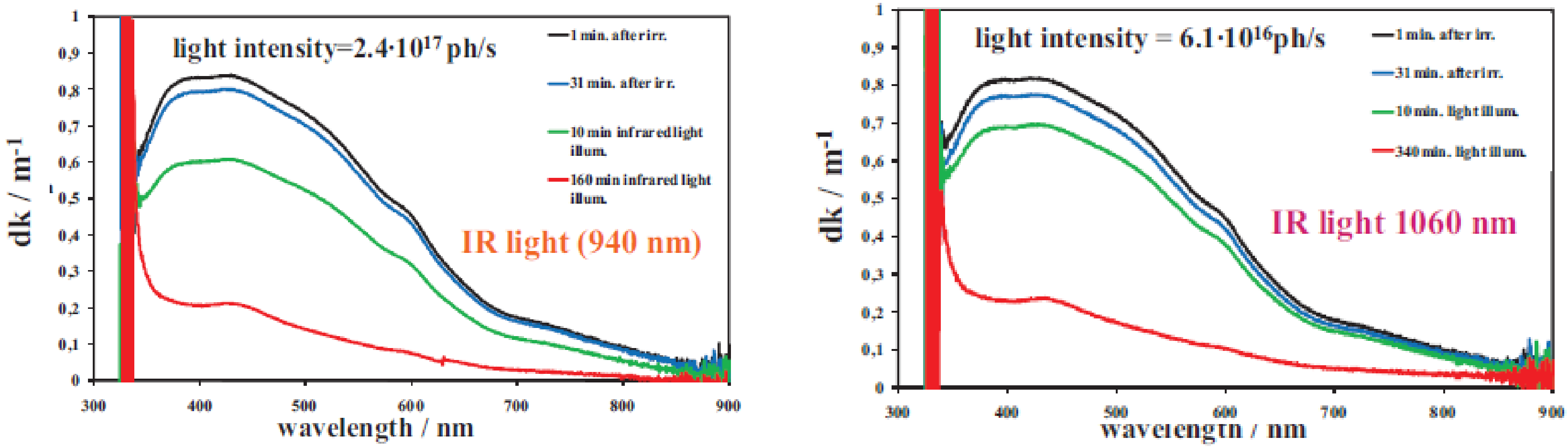


IR stimulated recovery of 3 krad radiation induced normalized LO of PbWO crystal .

- **IR curing can be performed continuously, even with PMTs on**
- **Need light intensity ~10^{16} -10^{17} photon/s per block, (can be supplied by LEDs)**
- **Method with IR light is still in development stage and more studies needed**

Simulated recovery of the $PbWO_4$ with IR light λ > 900 nm

Studies performed by PANDA collaboration



Recovery of 3 krad radiation induces absorption coefficient dk stimulated with infrared light of wavelength λ=940 nm (left) and λ=1060 nm (right). (*R. W. Novotny, IEEE-2009-05402124).*

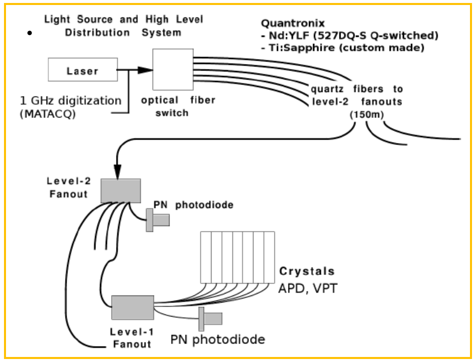
Good recovery can be achieved illuminating crystals with IR light even with higher wavelength (~1000 nm). **Method is still in development stage, but very promising**!

If this method practically will work, then:

▪ At dose rates of ~1 krad/h with a IR light of λ~940 nm and intensity ~2×10^17 γ/s one may continuously recover degradation of the crystal in curse of the experiment

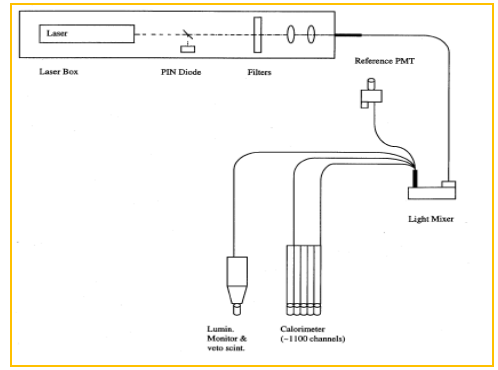
NPS Calorimeter Light Monitoring System

The CMS laser base monitoring system.

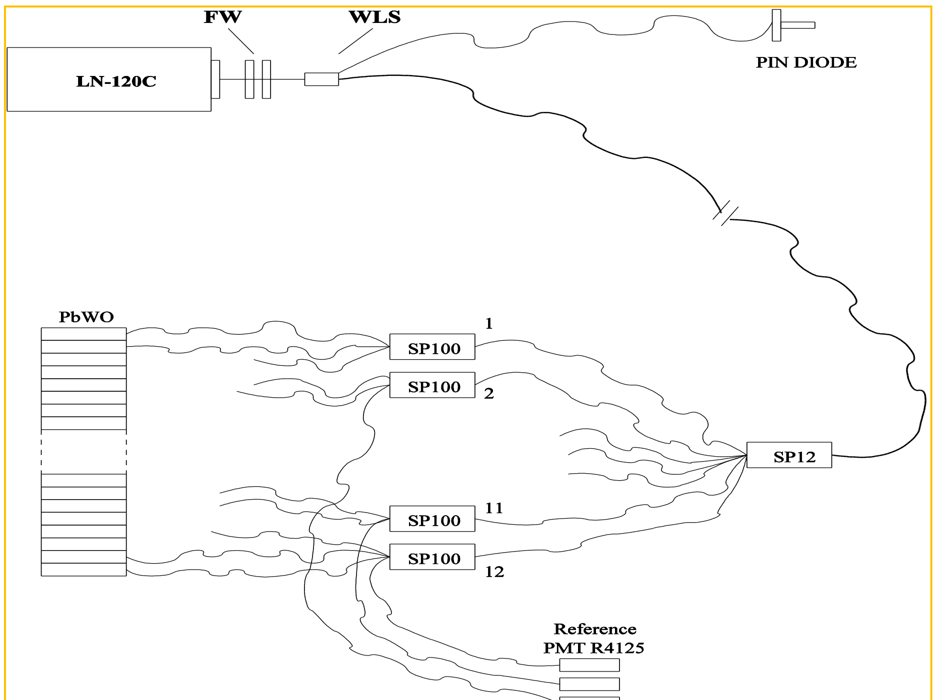


(F. Ferri, J. Phys. Conf. Ser. 404 (2012) 012041).

PrimEx laser base gain monitoring system



(Adopted from PrimEx CDR)).



For NPS calorimeter monitoring will use traditional system which include:

- Light source (Laser or set of LEDs),
- Wheels with a neutral density filters
- Wave Length shifter (if using UV light) or mixer (if light source will be set of LEDs),
- Light distribution boxes (1^{st} & 2^{nd} step)
- Reference Photodiode and PMTs .
- Primary and secondary fibers

NPS Calorimeter Light Monitoring System

▪ A light monitoring system will measure variation of the transmittance of crystals in the course of experiment and provide calibration in situ.

▪ It will inject light into detector modules during special calibration runs and be used to define calibration constants and adjust gain (high voltage) of PMTs.

▪ Up to sum level of accumulated radiation doses (a few tens of krad) would be possible to keep performance of the calorimeter acceptable for the experiments by calibration and optimization of the PMTs gains (HV).

▪ Since most of the radiation damage is occurred in the first 2-3 cm of the front of the crystal, monitoring of this damage does not give information about transmittance of the crystal, but will help to monitor condition and define when curing is needed.

▪ Light monitoring system of the NPS calorimeter would be clone (or very similar) to the system used for Hall C calorimeters and neutron detector, and systems developed for CMS, ATLAS, PrimEx or other calorimeters.

NPS Calorimeter Curing System

▪ The loss of signal amplitude from a calorimeter module is due to degradation of the transmission properties of the $PbWO_4$ crystals, but not because of degradation of the PMT photocathode or change in scintillation mechanism.

▪ It is possible to cure radiation damage by optical bleaching (exposing high intensity blue light). This will required interruption of data taking and Hall access.

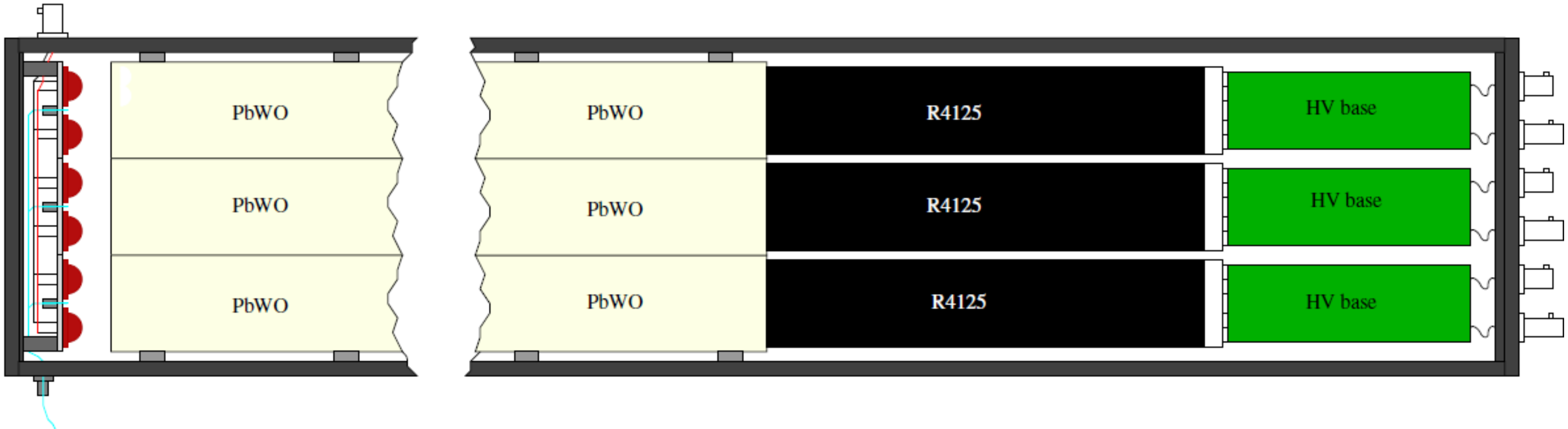
▪ It may well be possible to do such a curing cycle during an opportunistic beam studies or beam down times (or pass/energy changes).

▪ Best would be continuous curing with IR light (with a λ out of the PMT quantum efficiency range), without interruption of the experiment and need of Hall access. But such method currently is under development stage, and needs more studies.

▪ There are also technical problems how to deliver light from monitoring and curing systems to the crystals, taking into account actual physical dimensions of the crystals, PMTs.

NPS Calorimeter Prototype

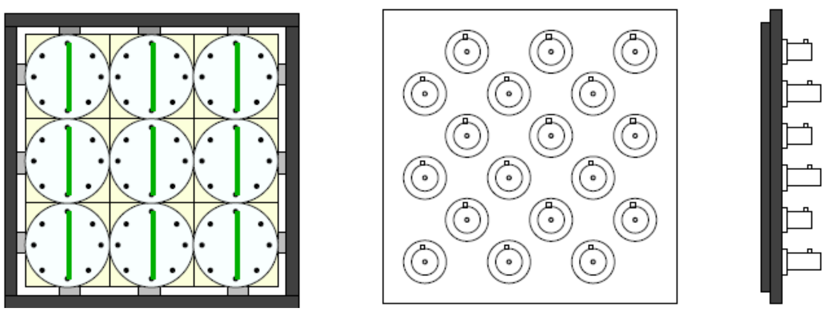
Since many technical aspects of the calorimeter are new, and some are at the development stage, we are planning to build a prototype, in order to study all technical problems before finalizing the design of the NPS calorimeter.



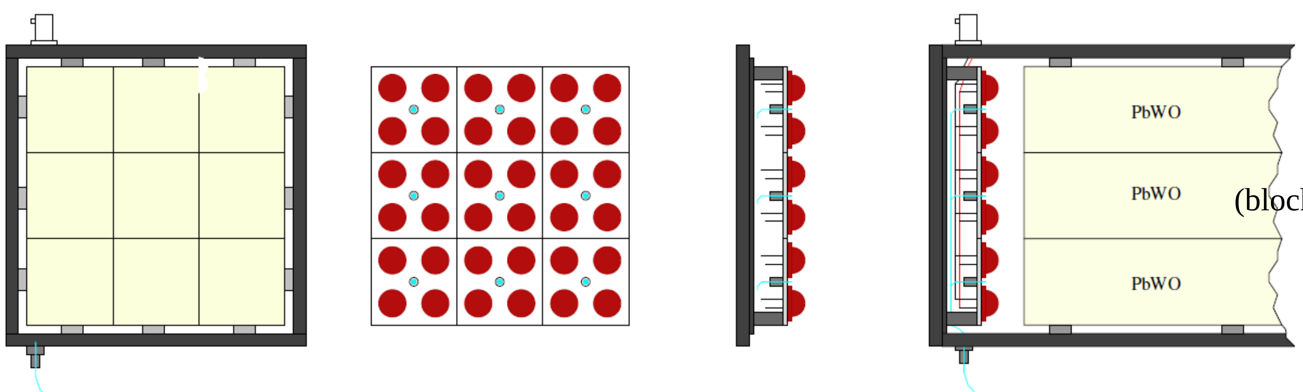
- The prototype would be matrix of 3×3 $PbWO_4$ crystals, each 2.0×2.0×20.0 cm^3
- It will have Monitoring system based on Blue Light source (matrix of LEDs)
- For the curing of the crystals we are considering to build two separate systems:
  - traditional, based on a blue light source (λ~460 nm), and
  - new and currently at development stage, Infra-Red curing (λ>800 nm)
- Currently we are working on design of the prototype, and looking for the components of monitoring and curing systems.
- We also are working on the list of proposed tests, and equipments needed.

More details of the NPS Calorimeter Prototype

Side view
(blocks, PMTs and HV divider are shown)



Back view
(Dividers, signal & HV connectors are shown)



Front view
(blocks & LEDs are shown)

Current status of the Prototype

- 10 $PbWO_4$ crystals (2.0 cm × 2.0 cm × 20 cm) have are ordered (SICCAS, China)
- 10 PMT Hamamatsu R4125 are ordered (Hamamatsu, Japan)
- 10 Blue LED SLA580BCT3F (clone of NICHIA) have been ordered and delivered
- Two sets of IR LEDs (OSRAM SFH4233 and LD274-3) have been ordered and delivered
- Small correction in active HV divider implemented. We got quotation for 10 divider boards
- Looking for the electronic components for the dividers
- Looking for the types of Blue and IR LEDs
- Working to finalize the design of the prototype
- Have preliminary agreement with RadCon group (David Hamlett) to radiate two small pieces of $PbWO_4$ crystals up to accumulated doses of ~20 krad for future test of the curing systems
- Have preliminary agreement with Carl Zorn to be involved in our activities and tests

Preparation works and Proposed Studies with the Prototype

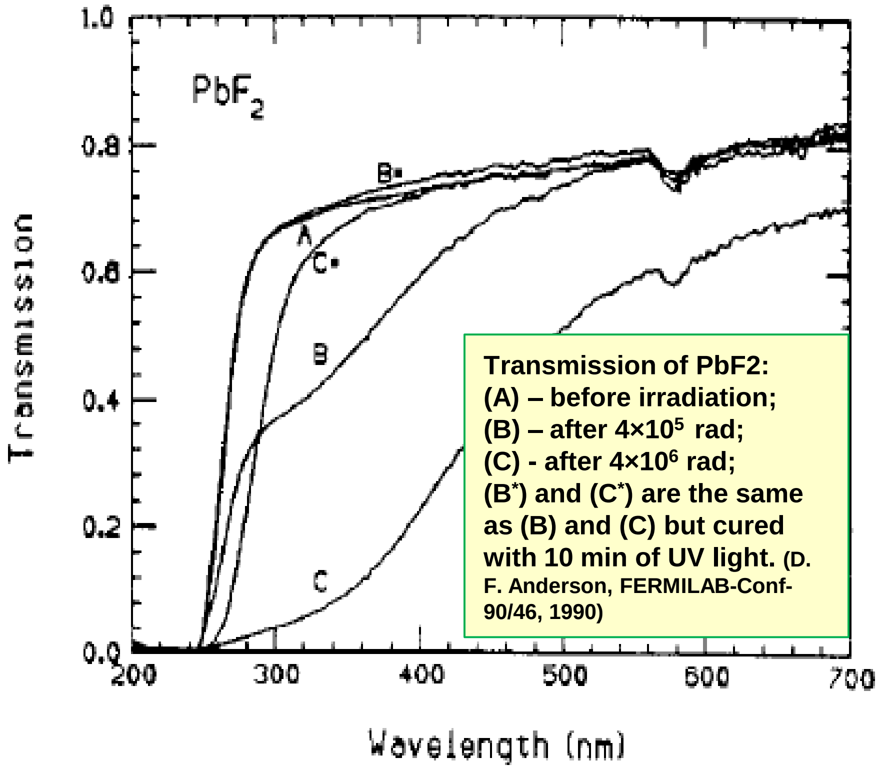
- **Assembling and test 10 HV active bases (dividers with amplifiers)**
- **Finalize design of the prototype (depending on actual dimensions and type of LEDs.)**
- **Studies of Blue and IR LEDs (define their actual power, thermal heat and safety)**
- **Study of R4125 phototube QE for the light of wavelength in the range 900-1000 nm**
- **Measurement the light Transmission efficiency for the two pieces of PbWO before radiation and after radiation (depending as soon we can get them back from RadCon)**
- **Use Prototype curing systems for recovery of the crystals (with Blue and IR lights).**
- **Perform light Transmission efficiency measurement after curing of the crystals and compare this with the transmissions before and after irradiation.**
- **Finalize design, mount and test curing systems (Blue and IR)**
- **Assembly and test Light Monitoring System (based on matrix of Blue LEDs)**
- **Design temperature controlled frame for the prototype**

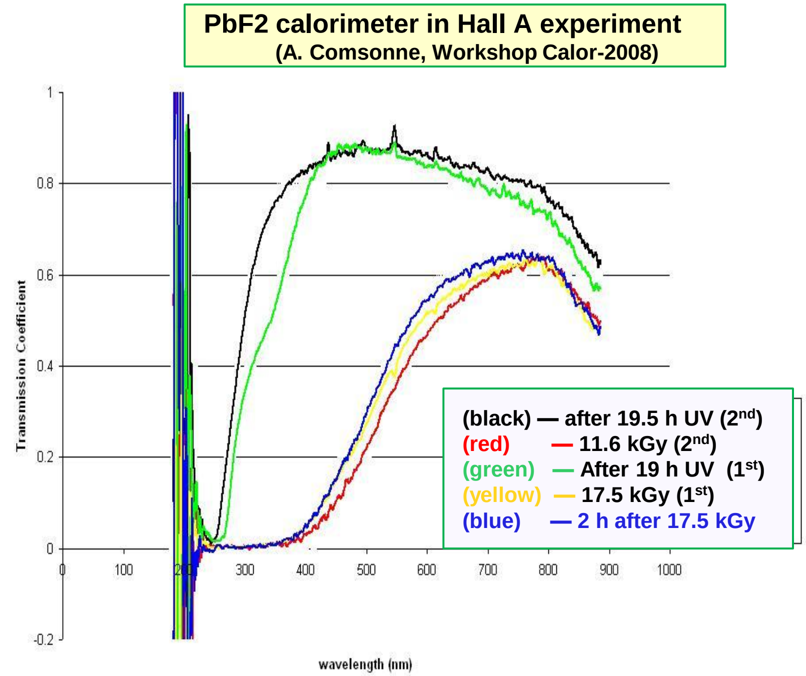
All this point we have just raw and preliminary ideas and are still at the development stage. We count on your comments, advises and critics.

Thanks for Your Attention !

There are many open issues and problems where we need your help and comments !

Simulated UV-recovery radiation damage of PbF_2





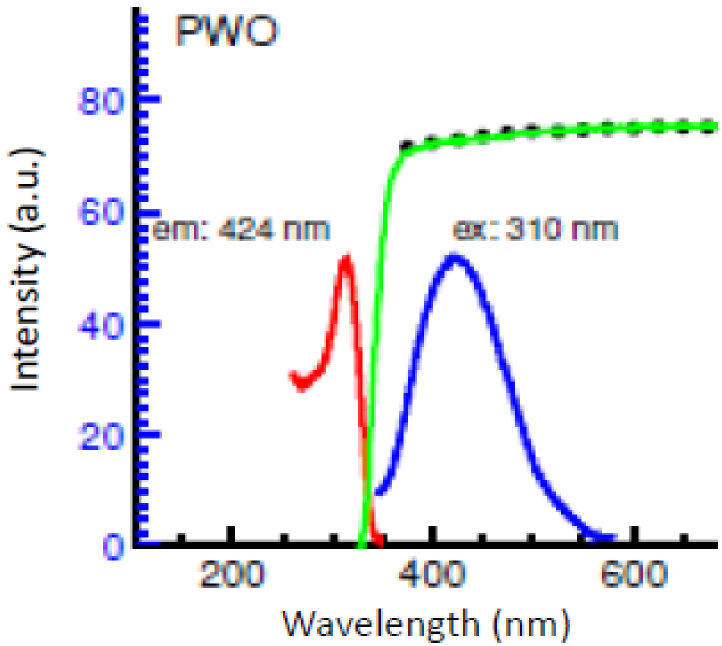
- **PbF_2 degradates by 5-10% (at $\lambda > 350$ nm) below 5-10 krad integrated doses.**
- **Damage of PbF_2 crystal can reach 20-30% at doses ~30-50 krad.**
- **For integrated doses of 1-2 Mrad the radiation damage is significant**
- **The damage of PbF_2 crystal can be easily removed by UV optical bleaching.**

$PbWO_4$ properties

Property	Value
Density (g/cm^3)	8.3
Radiation length (cm)	0.89
Moliere radius (cm)	2.00
Interaction length (cm)	20.7
Refractive index (420 nm)	2.20
Hygroscopicity	No
Luminescence (nm), slow and fast components	~425, ~360
Decay time (ns) slow and fast components	30, 10
Light yield (% of NaI) slow and fast components	~0.30, 0.077
dLY/dT (%/C) at room temp.	-2.5

Good: dense, fast, not hygroscopic

Bad: temperature dependent LY



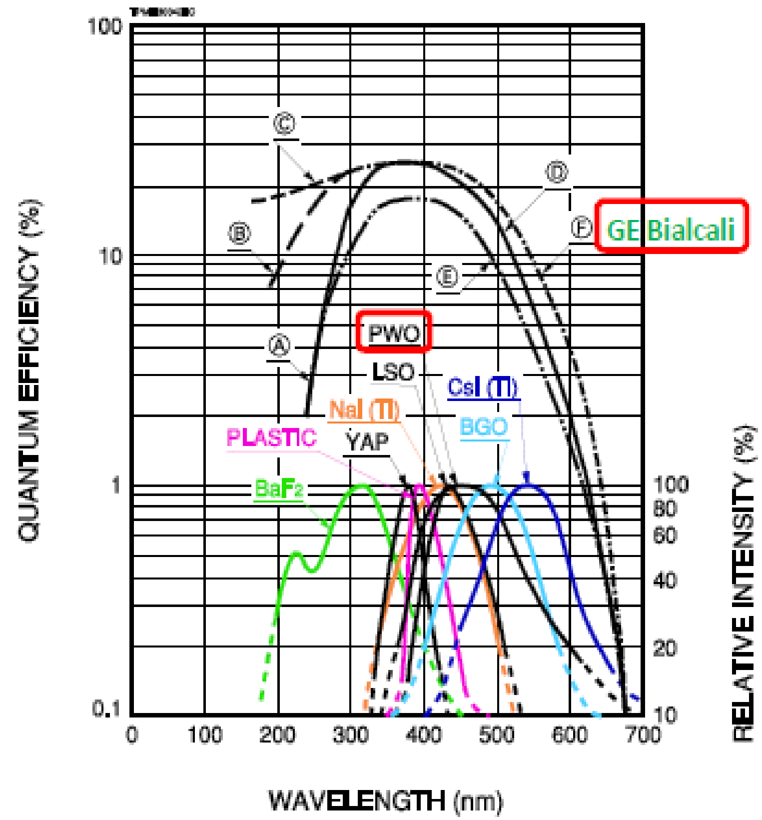
The excitation (red), emission (blue) and the transmittance (green) spectra of $PbWO_4$

Emission spectrum is in the transparent region, thus no self-absorption. Detectors of extended size can be built.

Choice of PMT for $PbWO_4$

Hamamatsu R4125 PMT (used in PrimEx), may be a good choice.

Parameter	Value
diameter	18.6 mm (3/4'')
No. of stages	10
Photocathode	Bialkali, Green Ext.
Sensitivity range	300 – 650 nm
QE max at ~400nm	27 %
Supply voltage	1500 V
Gain	8.7×10^5
Dark Current	10 nA
Rise Time	2.5 ns
Transit Time	16 ns

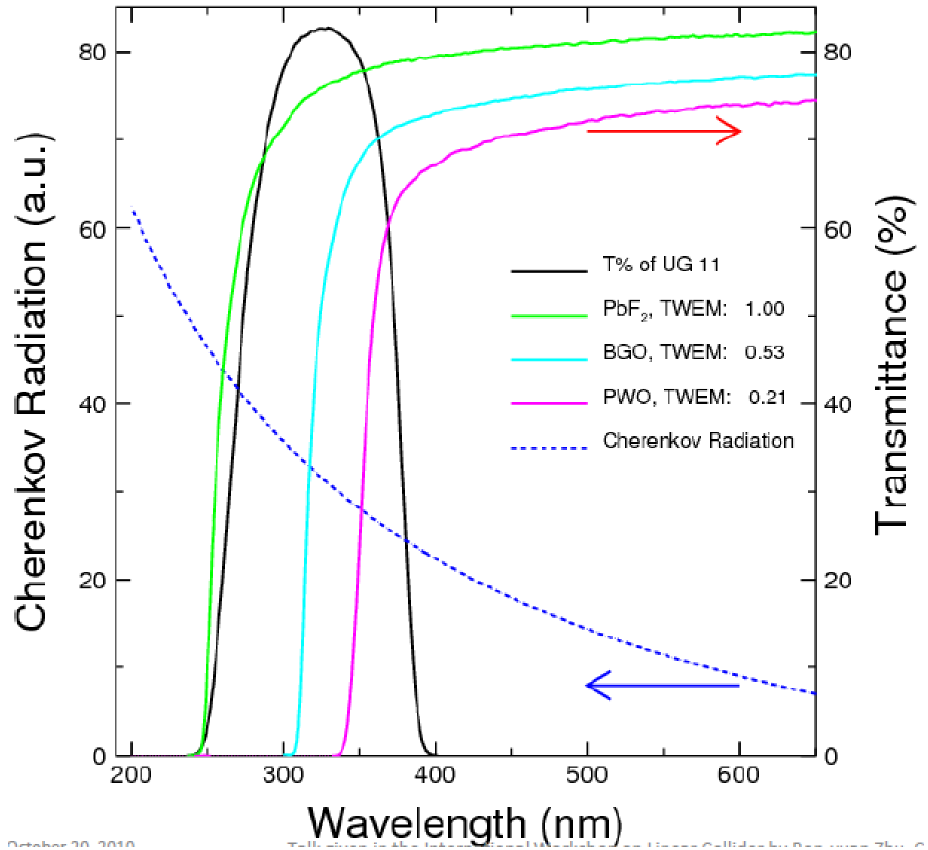


Sensitivity range of R4125 matches range of emission of $PbWO_4$

PbF_2 properties

Property	Value
Density (g/cm³)	7.77
Radiation length (cm)	0.95
Moliere radius (cm)	2.22
Interaction length (cm)	~21.0
Refractive index (420 nm)	1.82
Hygroscopicity	No
Luminescence (nm), slow and fast components	~310, ~280
Decay time (ns) slow and fast components	< 30
Light yield (% of NaI) slow and fast components	~0.05
dLY/dT (%/C) at room temp.	-0.2

(From R. Zhu, ILC workshop, CERN, 2010)



Transmittance of PbF_2 (**green line**) is suited for the Cherenkov light spectrum (blue dotted).

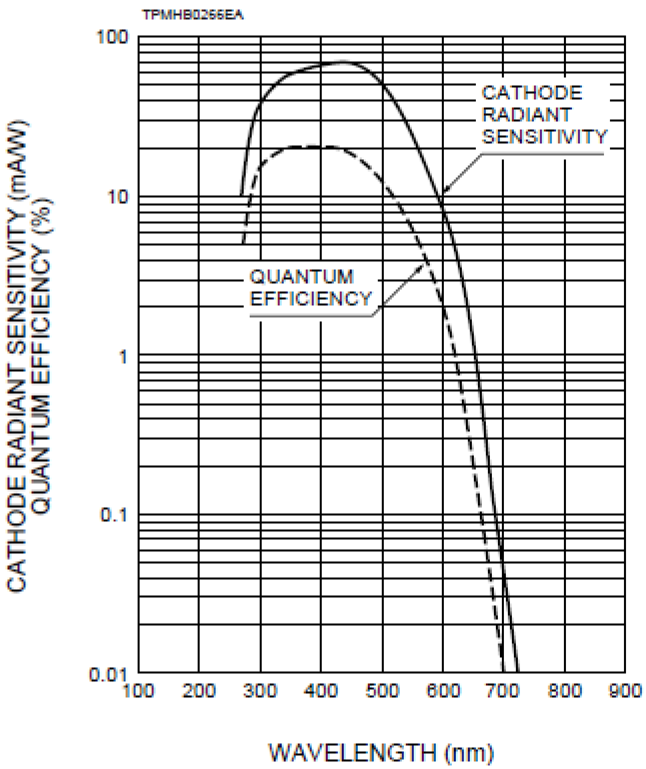
Good: dense, fast, not hygroscopic, no temp. dependence.

Bad: low Light Yield

Choice of PMT for PbF$_2$

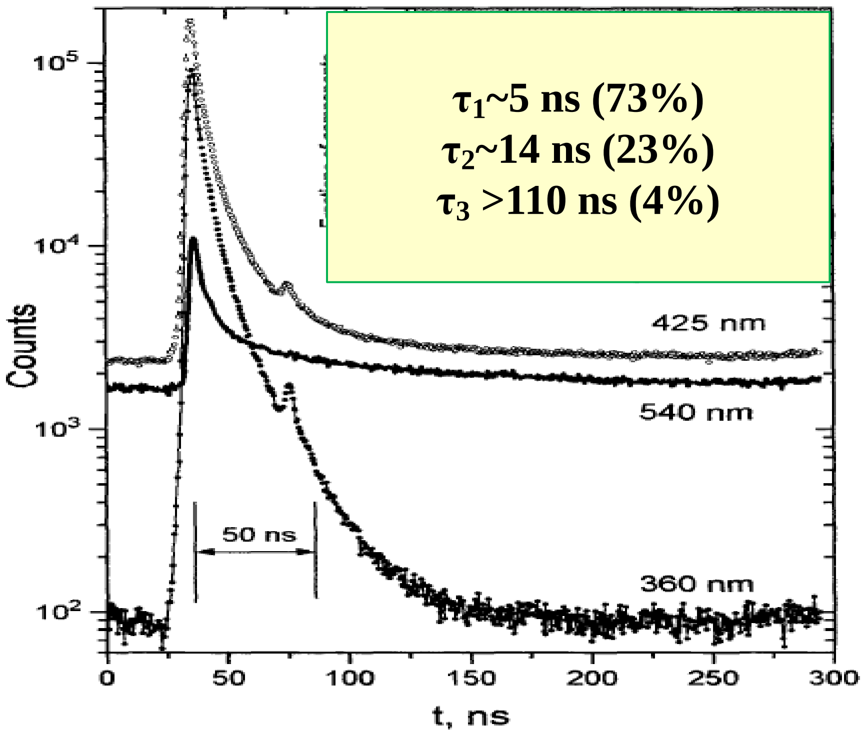
Hamamatsu R7700 PMT (used in Hall A).

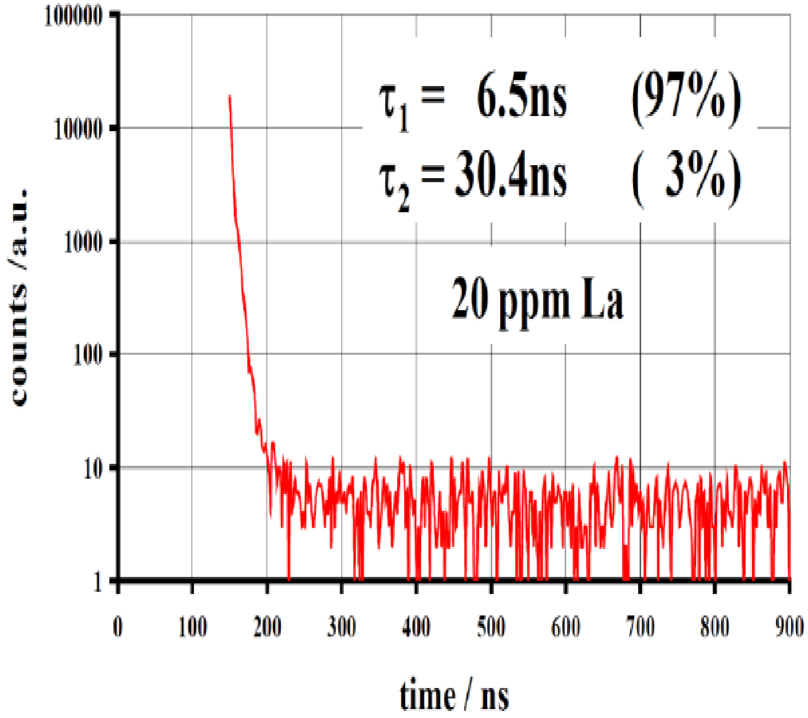
Parameter	Value
Effective area	22 mm×22mm
No. of stages	8
Photocathode	Bialkali
Sensitivity range	300 – 650 nm
QE max at ~400nm	20 %
Supply voltage	900 V
Gain	10^4
Dark Current	~2.0 nA
Rise Time	1.2 ns
Transit Time	< 1 ns



Sensitivity range of R7700 matches range of emission of PbF$_2$

Decay time for the emission of $PbWO_4$

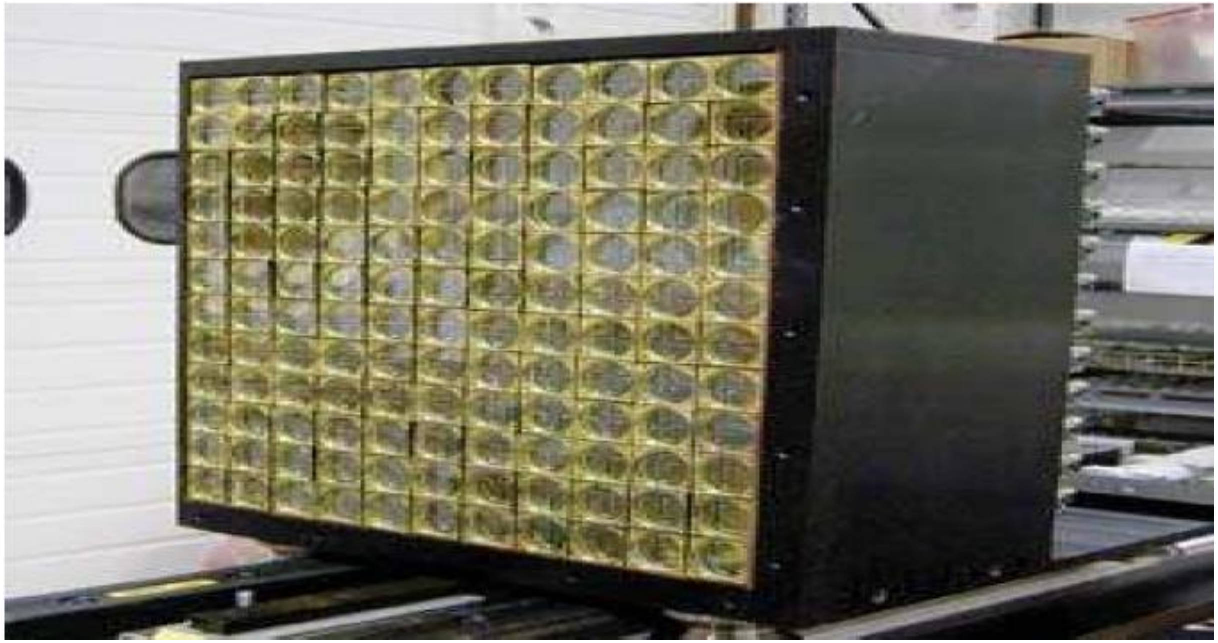




The emission of $PbWO_4$ includes three components:
τ_1 ~5ns (73%), has values 0.6, 1.8, 2.3 11.9 ns;
τ_2 ~14 ns (23%) has 3.44, 5.16, 20.54, 60.6 ns;
τ_3 >110 ns (~4% of the total intensity).
(A. N. Belsky et al., Chem. Phys. Lett. 243 (1995) 552)

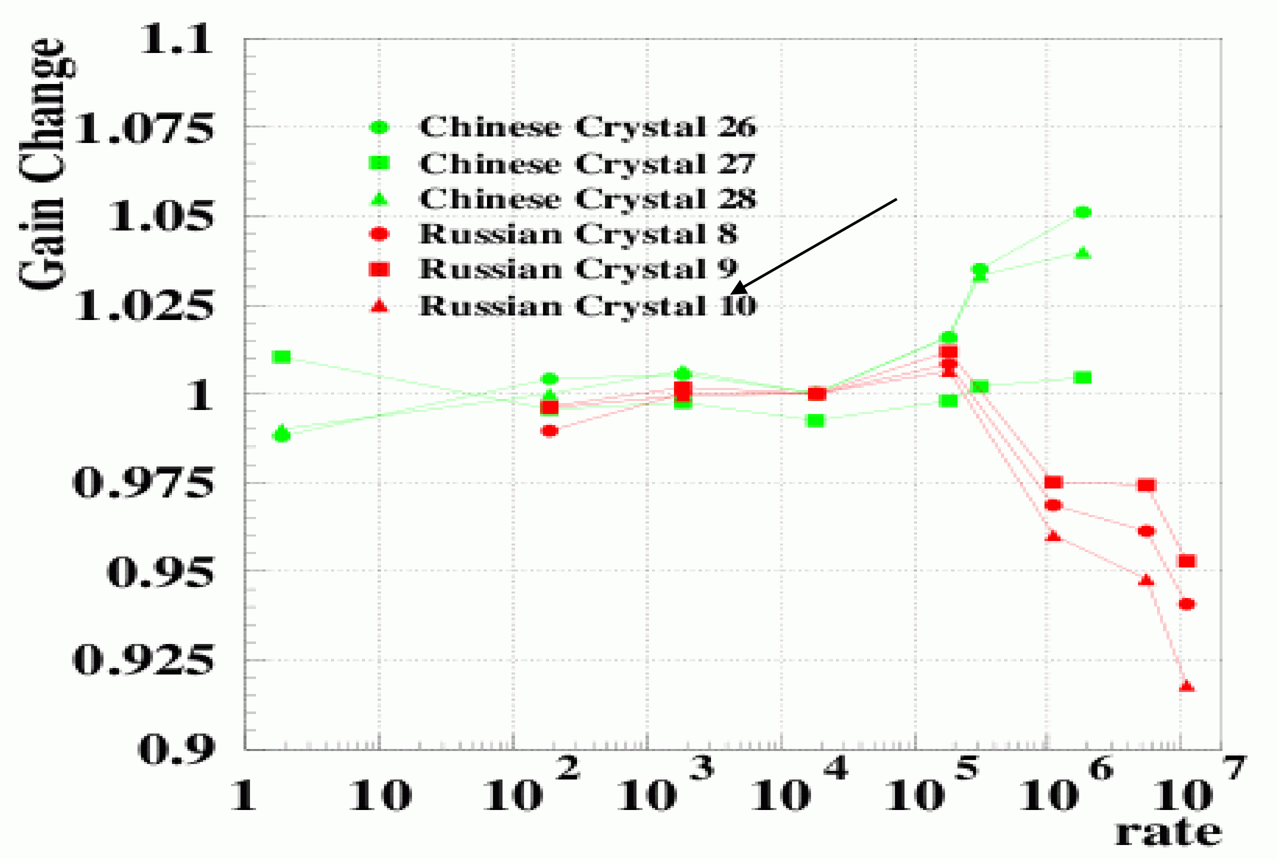
New $PbWO_4$ crystals for PANDA includes two emission components:
τ_1 ~6.5 ns (97%);
τ_2 ~30.4 ns (3% of the total intensity).
(R. W. Novotny, IEEE, NSS, 2003)

PbF$_2$ calorimeter in Hall A DVCS experiment



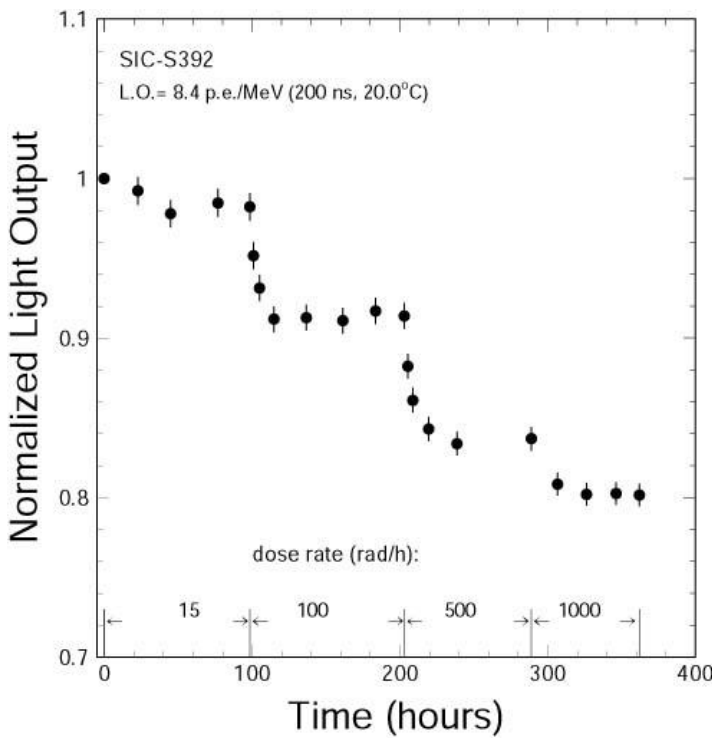
Visual inspection of PbF_2 blocks after Hall A first DVCS experiment. The darkness of some blocks on the target side (very evident for block 39) most likely is created by low energy electrons and photons. (From S. Gregoire report, August 16, 2007).

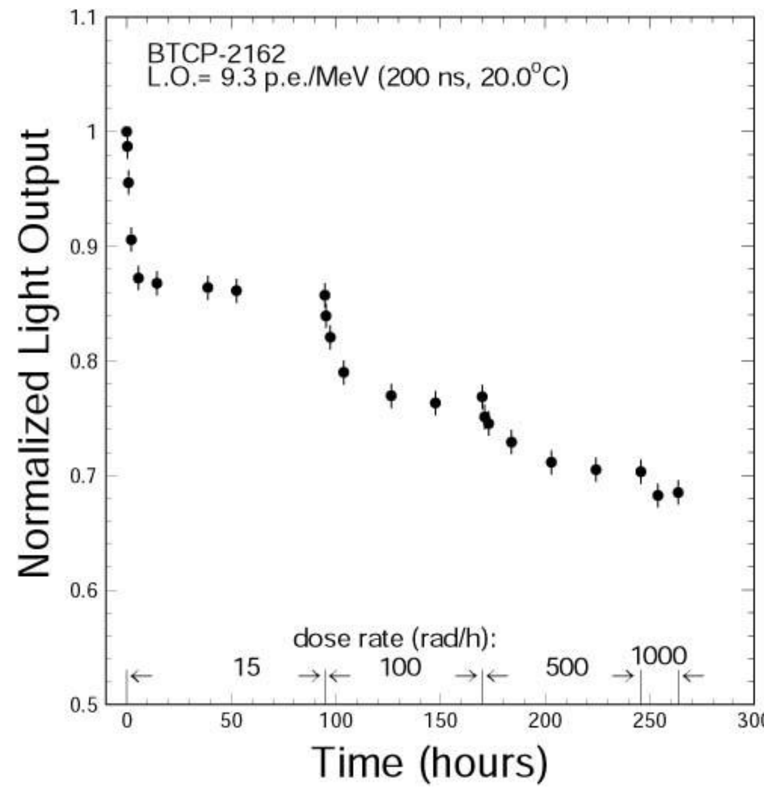
The PMT gain variation with rate



Variation of the Hamamatsu R4125 gain of $PbWO_4$ crystals with the rate (Tested by PRIMEX collaboration in electron beam test).

CMS PWO(Y) Crystals Radiation Damage

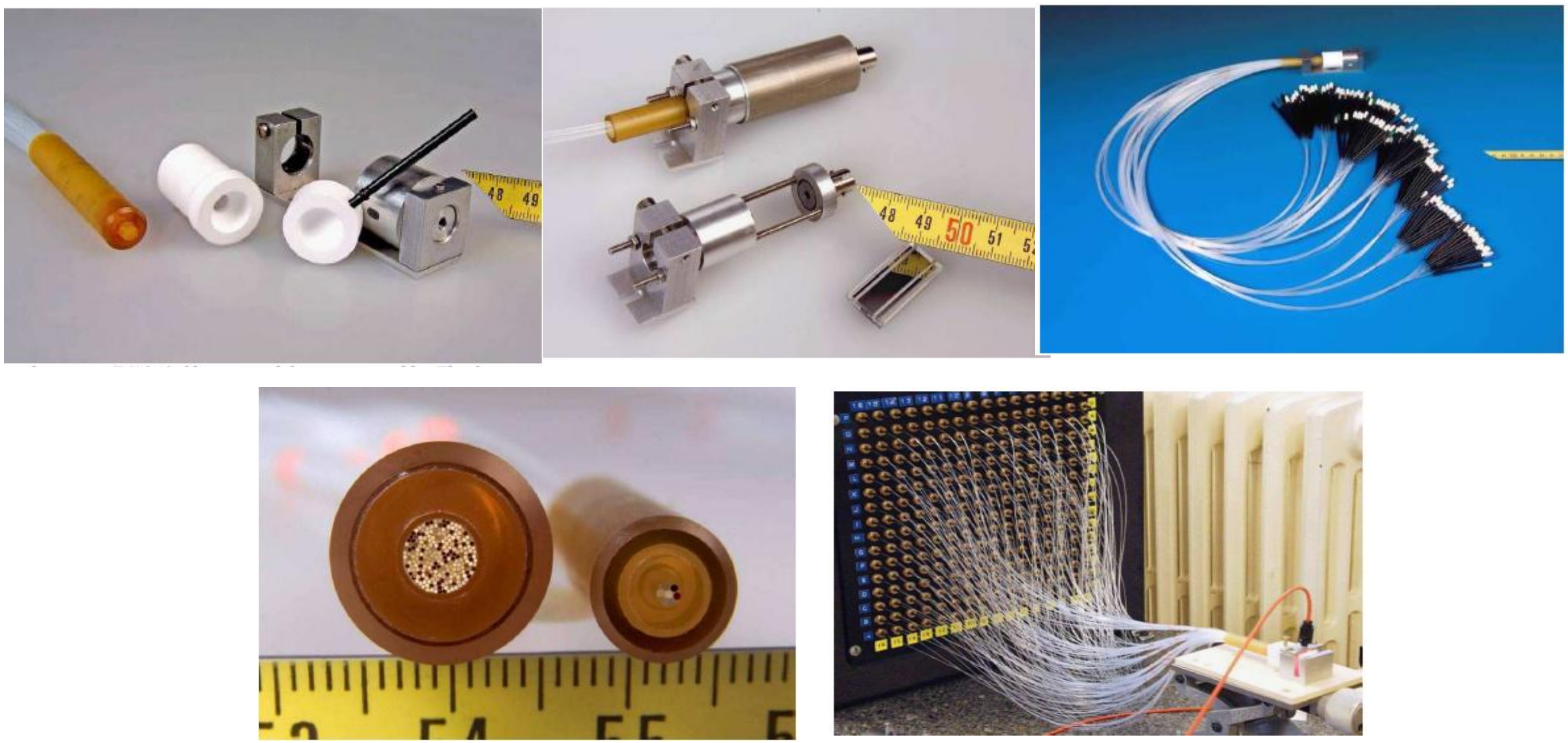




(From R. Y. Zhu presentation, ILC workshop, Caltech, 8 jan, 2002)

Components of CMS Monitoring System

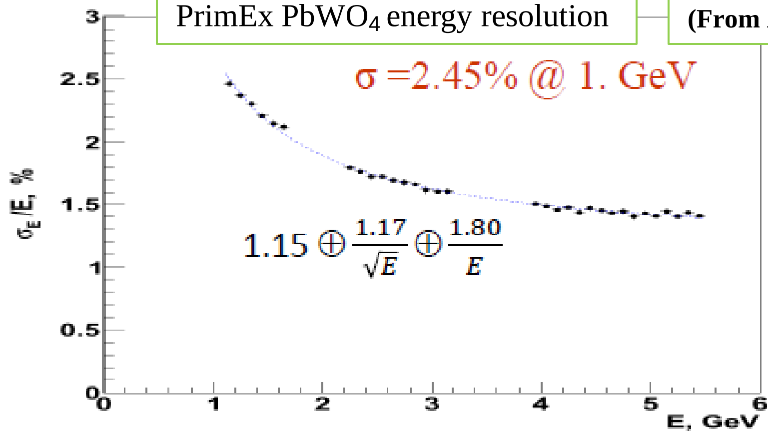
Many details and technical solutions of light monitoring system can be found and adopted from well-known calorimeters, such as PANDA, PrimEx, ATLAS and CMS. As an example in figures below are shown some details of CMS laser based light monitoring system.



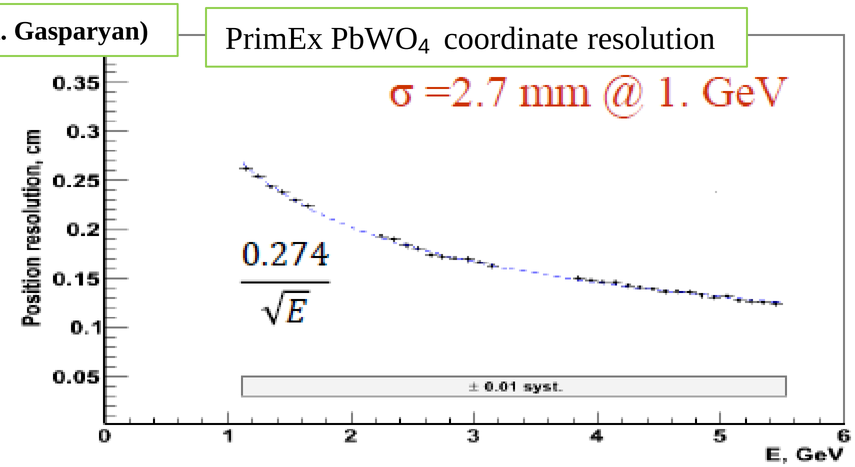
Some details of CMS calorimeter laser based monitoring system

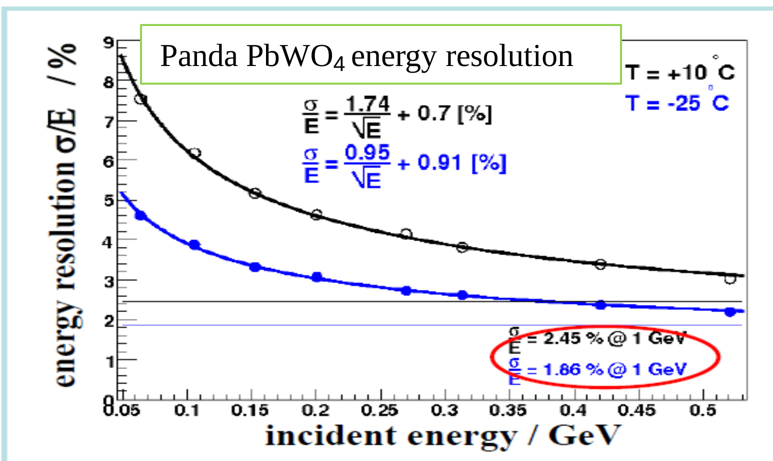
(Adopted from M. Anfreville et al., NIM A 594, 2008, p292)

Energy & coordinate resolutions $PbWO_4$ and PbF_2

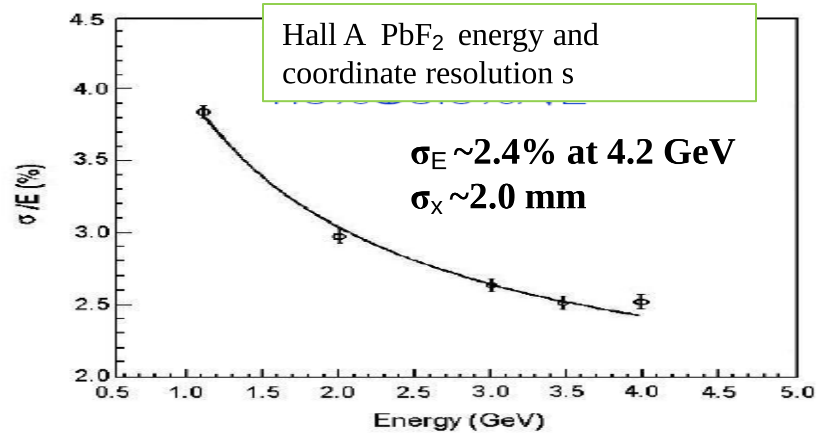


(From A. Gasparyan)





(From Z. Tianchi, Calor-2011)

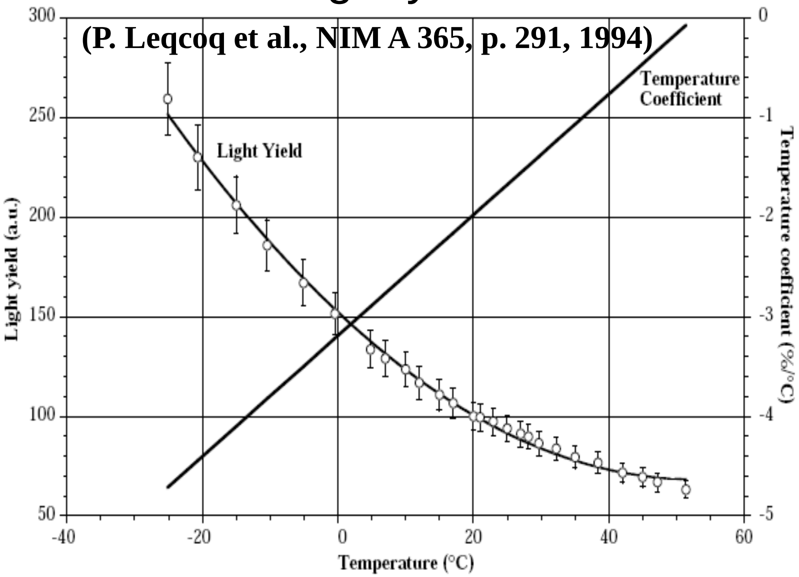


(From K. Jager, Hall A Status Report-2002)

$PbWO_4$ and PbF_2 calorimeter with fine granularity of crystals (2×2cm² – 3×3cm²) can provide energy resolution better than 3% and coordinate resolution ~2-3 mm

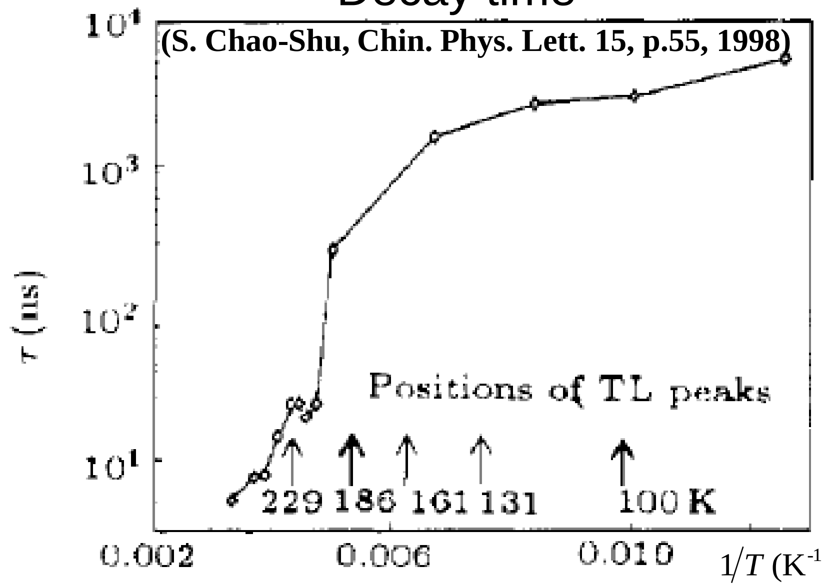
Temperature dependence of $PbWO_4$

Light yield



Temperature dependence of the light yield and temperature coefficient of the $PbWO_4$

Decay time



Temperature dependence of the decay time of the emission of the λ=430 nm from $PbWO_4$

- The light yield increases at low temperature, but with increasing the luminescence decay time and decreasing radiation resistance of the $PbWO_4$.

- For the $PbWO_4$ crystals need Temperature controlled frame.

- The light yield and decay time of PbF_2 nearly independent on temperature.

Requirements of the experiments

Parameter	DVCS (E12-13-010)	DVCS (pol. 3He)	WACS (PR12-12-009)	DES π^0 (E12-13-010)	SIDIS π^0 (E12-13-007)
Min. dist. From. Tgt. (m)	~3.0-6.0	~3.0-4.0	3.0-5.0	4.0	4.0
Coordinate res. (mm)	3-4	3-4	3-4	2-3	2-3
Photon angl. Res. (mrad)	1-2	1-2	1-2	0.5-0.75	0.5-0.75
Energy res. (%)	(5-6)/√E	~6/√E	~5/√E	(2-3)/√E	(2-3)/√E
Sweeping magnet (Tm)	0.3	0.3	0.6	0.3	0.3
Second arm	HMS	HMS	HMS	HMS	HMS
Photon angle (degrees)	6.0-23.0	6.0-25.0	22-60	10-25	6.0-23.0
Photon energies (GeV)	2.7-7.6	3-7	1.1-3.4	3.1-5.7	0.5-5.7
Acceptance (msr)	~10	~10	~10	~25	~25
Beam current (μA)	5-10	~60	~40, +6%Cu	1-2	1-2
Targets	10cm LH2	30cm 3He	15cm LH2	10cm LH2	10cm LH2
Luminosity ($cm^{-2}s^{-1}$)	$\sim10^{38}$	$\sim10^{37}$	$\sim10^{39}$	$\sim3x10^{37}$	$\sim3x10^{37}$
Rates & Timing	~1-2MHz <100ns	~100ns	~100ns	~1-2MHz <100ns	~1-2MHz <100ns
Beam Time (hours)	~1200	~500	~1000	900	600
Expected total rad. Dose (Krad)	~200	<20	<20	~40-50	~40-50

- **Energy resolution ➔ high light yield, best available crystals**
- **Coordinate resolution ➔ fine granularity, small Møller radius, best 2x2 cm^2 or 3x3 cm^2**
- **Angular resolution ➔ combine fine granularity with distance from the target**
- **Good Timing ➔ Fast signal with short tail to minimize pile-up at high rates**
- **Radiation hardness ➔ Modest damage for integrated doses ~20-30 krad**

General properties of heavy crystals for calorimetry

Parameter	Lead Tungsten (PbWO4)	Lead Fluoride (PbF2)	Bismuth Germanate (BGO)	Luterium-Yttrium (LSO/LYSO)
Density (g/cm³)	8.28	7.66-7.77	7.13	7.2-7.4
Rad. length (cm)	0.89	0.93-0.95	1.10-1.12	1.16
Refraction index	2.20	1.82	2.15	1.82
Emission peak (nm)	420	~310, ~280	480	420
Moliere radius (cm)	2.19	2.22	2.15	2.07
Radiation type	Scint. (~13% Č)	Pure Čer.	Scint. (~1.6% Č)	Scintillation
Timing property τ (ns, %)	5(73%), 14(23%), 110(4%)	Fast, <30	300	40-50
Effective Z	73	77	83	65
Hydroscopicity	No	No	No	No
Interact. length (cm)	~20.7	~21	~22.7	~20.9
Rad. hardness (krad)	~20-50	~50	~1,000	>1,000
Light yield LY (photon/MeV)	~140-200	~2-6	~5,000-10,000	~5,000-30,000
d(LY)/dT (%/°C)	-2.0-2.5	No	-0.9	-0.2
Critical energy (MeV)	~9.6	8.6-9.0	7.0	9.6

BGO, $PbWO_4$, PbF_2 and LSO/LYSO are among the good candidates

But BGO is too slow and LSO/LYSO are very expensive.

Our choice would be to use $PbWO_4$ or PbF_2, or their combination

Temperature Controlled Frame for the NPS Calorimeter

- The light yield and decay time of the $PbWO_4$ are temperature dependent, with the light yield increasing at low temperature (but the decay time drastically decreasing at room temperature).

- Given the temperature sensitivity of the scintillation light output of the $PbWO_4$ crystals, the entire calorimeter must be kept at a constant temperature, to within 0.1 ºC to guarantee 0.5% energy stability for absolute calibration and resolution.

- The NPS calorimeter will be thermally isolated and be surrounded on all sides by water cooled copper plates.

- This design is based on that of the HYCAL temperature controlled frame and optimized with more recent experience from CMS, which has shown stability to 0.05 ºC.