Comparison of $PbWO_4$ and PbF_2 crystal properties

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NPS Collaboration Meeting, Jlab, November 14, 2013

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 ($cm^{-2}s^{-1}$)	~10^{38}	~10^{37}	~10^{39}	~$3x10^{37}$	~$3x10^{37}$
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 achievable crystals**
- **Coordinate resolution** ➔ **fine granularity, small Moller 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**

Characteristics required for the crystals

- **Small Moliere radius and fine granularity for good position resolution**
- **High density for compactness of the detector**
- **Good optical transmission for light collection uniformity in long crystals**
- **Sufficient light yield for good energy resolution**
- **Short decay time for high rate capability**
- **Good resistance to radiation**
- **Possibility to remove the radiation damage easily in situ**
- **Relatively low cost**

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
Refractive 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, PbWO4, PbF2 and LSO/LYSO are among the good candidates

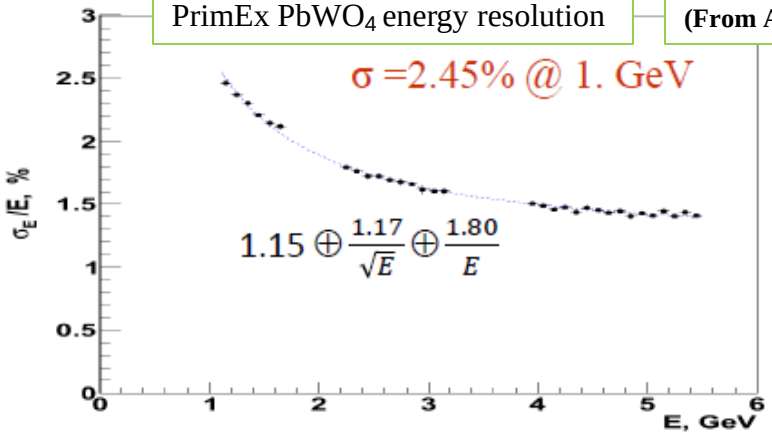
But BGO is too slow and LSO/LYSO are very expensive.

Our choice would be to use PbWO4 or PbF2, or their combination

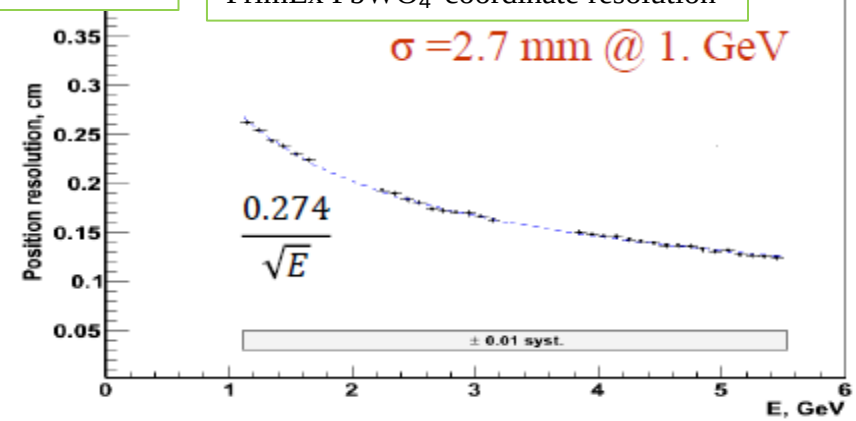
Energy & coordinate resolutions $PbWO_4$ and PbF_2

PrimEx $PbWO_4$ energy resolution

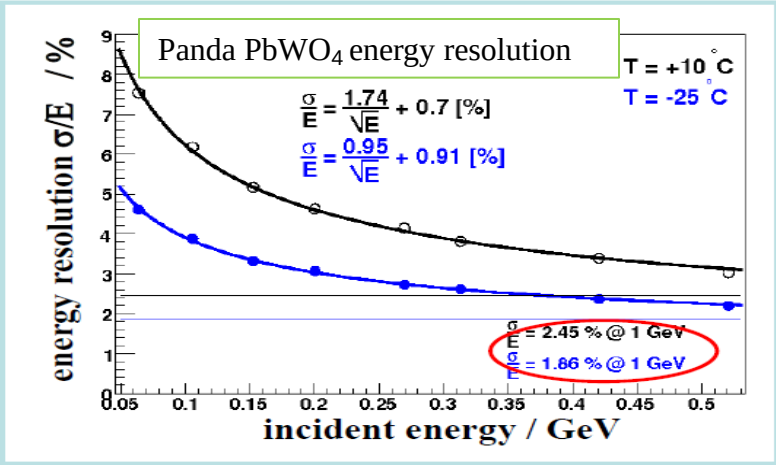
(From A. Gasparyan)



PrimEx $PbWO_4$ coordinate resolution

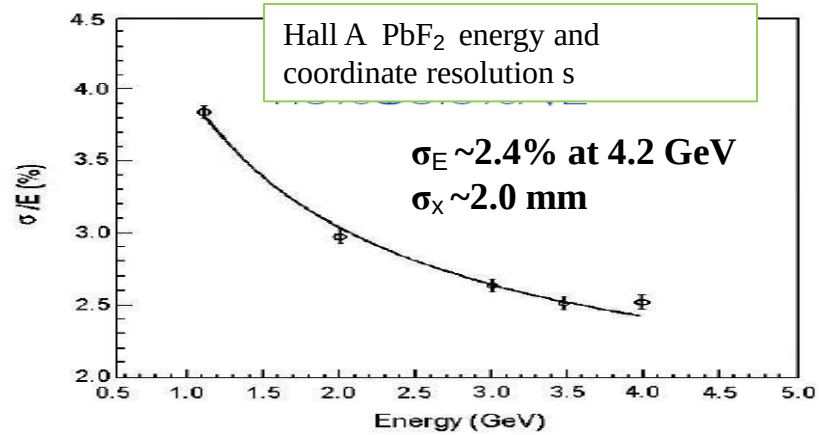


Panda $PbWO_4$ energy resolution



(From Z. Tianchi, Calor-2011)

Hall A PbF_2 energy and coordinate resolution s

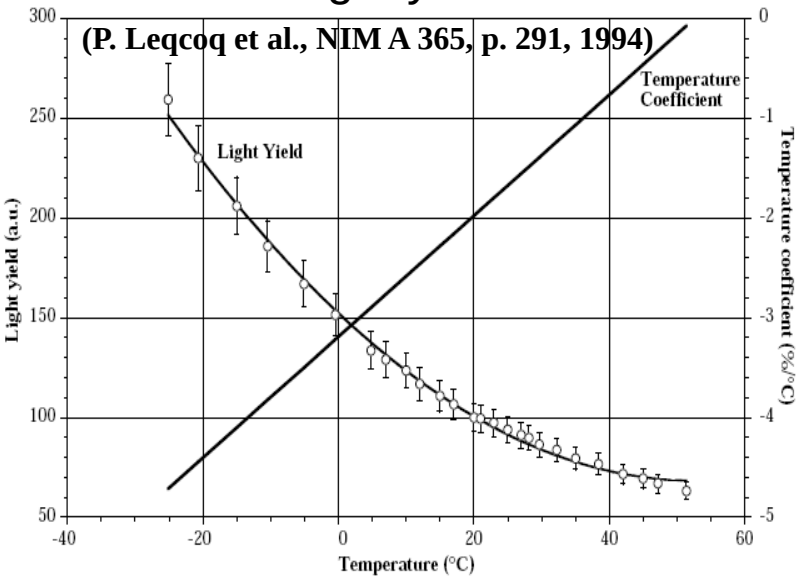


(From K. Jager, Hall A Status Report-2002)

$PbWO_4$ 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

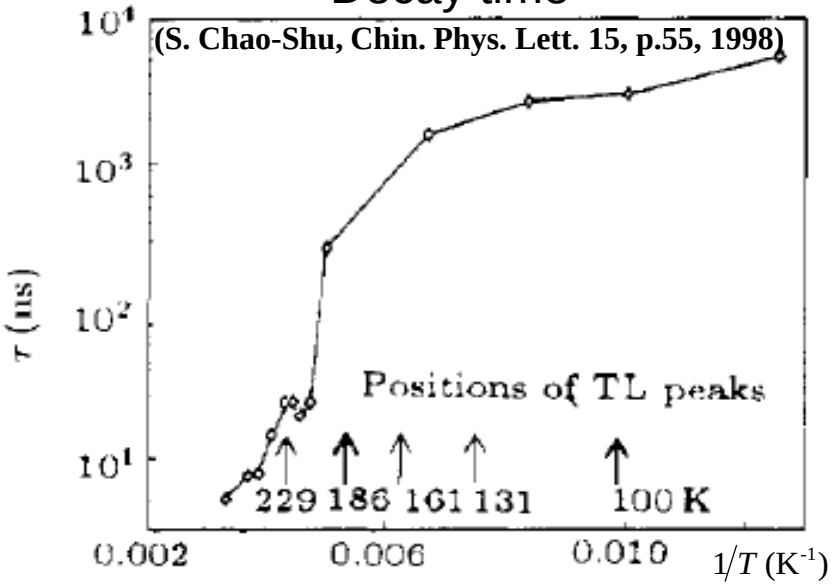
Temperature dependence of $PbWO_4$

Light yield



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

Decay time

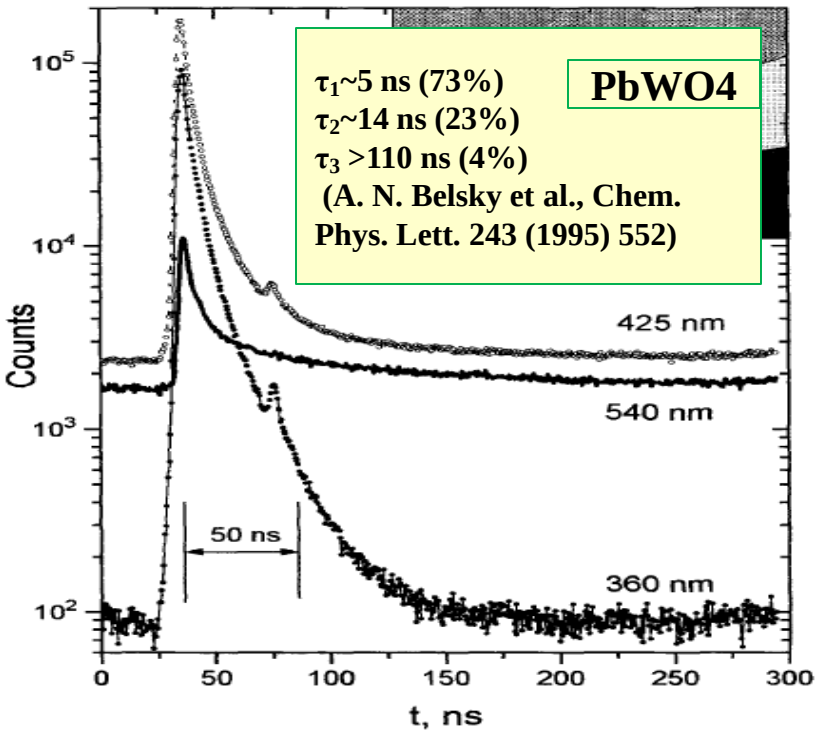


Temperature dependence of the decay time of the emission of the λ=430 nm from $PbWO_4$

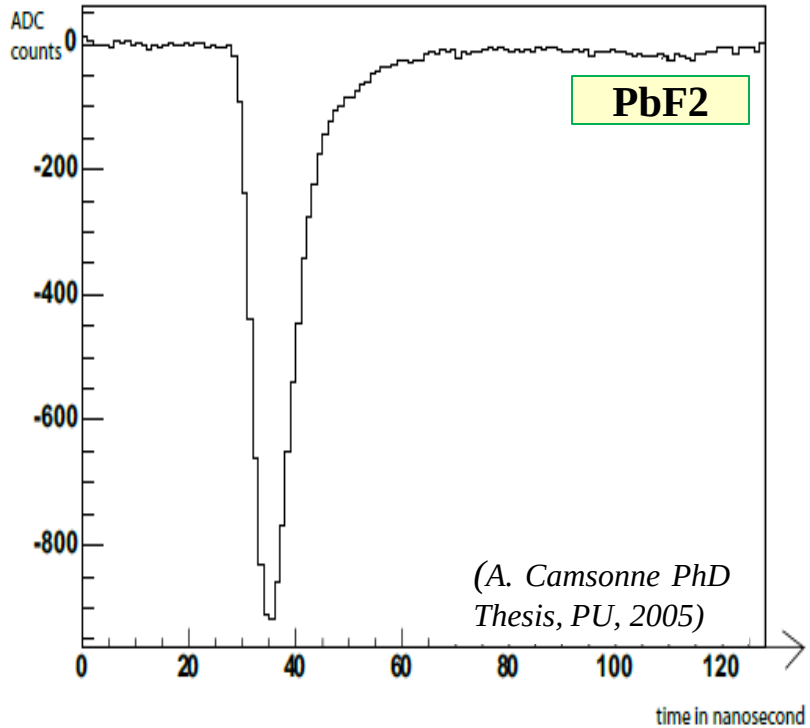
- The light yield increases at low temperature, but with increasing the luminescence decay time and decreasing radiation resistance of the $PbWO_4$.
- For the $PbWO_4$ crystals need Temperature controlled frame.
- The light yield and decay time of PbF_2 nearly independent on temperature.

Radiation type/Timing properties of $PbWO_4$ & PbF_2

The emission of $PbWO_4$ crystal



Typical signal from Hall A PbF_2 crystal



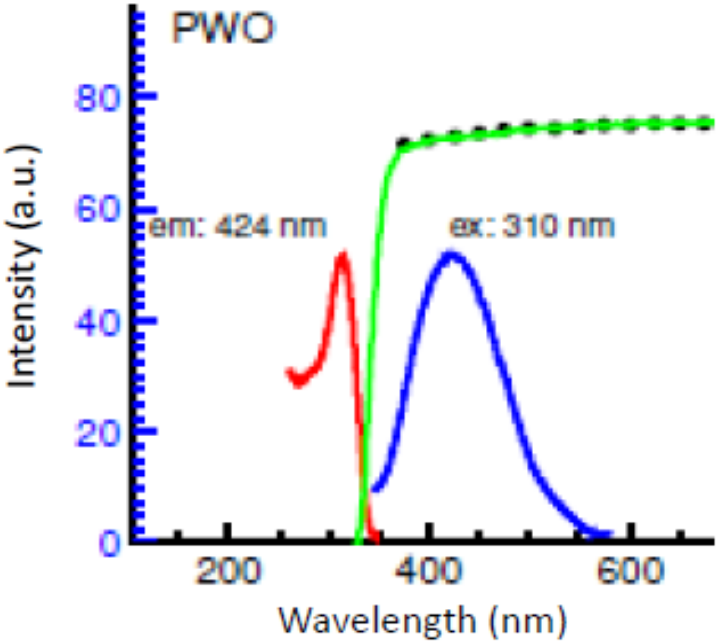
- **Light emission mechanism of $PbWO_4$ crystal includes Scintillation and Cherenkov (~10-20%).**
- **For the PbF_2 crystal the emission mechanism is pure Cherenkov.**
- **Both type of crystals are fast, but emission of $PbWO_4$ includes three components:**
  - **τ_1 ~5ns (73%), has values 0.6, 1.8, 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).**

$PbWO_4$ 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 hydroscopic

Bad: temperature dependent LY



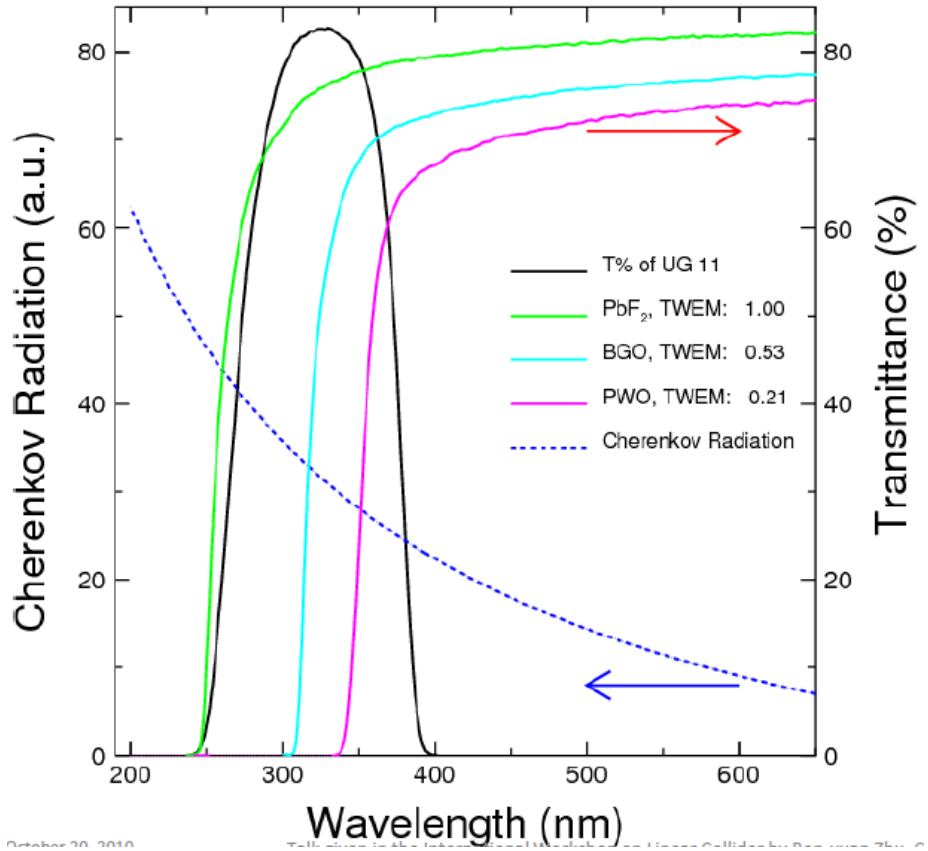
The excitation (red), emission (blue) and the transmittance (green) spectra of $PbWO_4$

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

PbF_2 properties

Property	Value
Density (g/cm^3)	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)



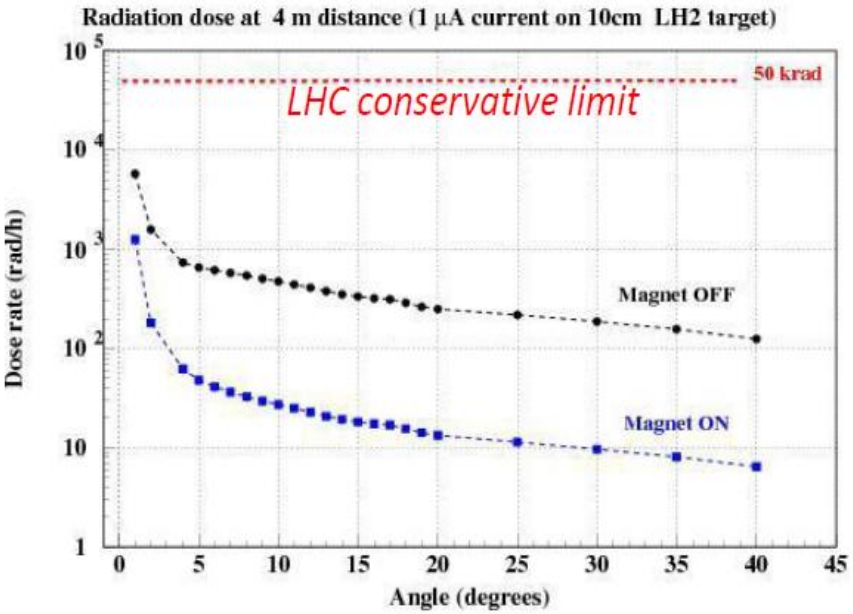
Transmittance of PbF_2 (**green line**) is suited for the Cherenkov light spectrum (blue dotted).

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

Bad: low Light Yield

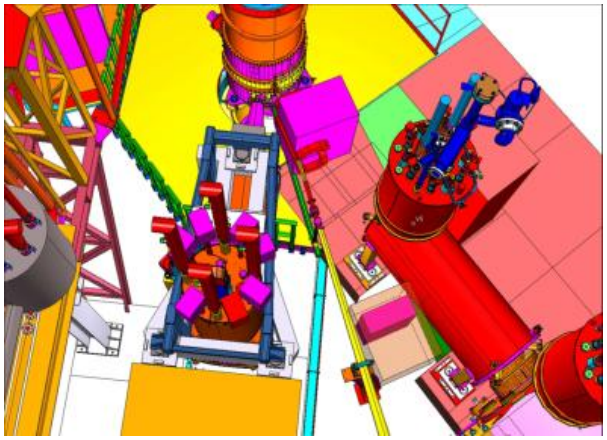
Radiation conditions in Hall C

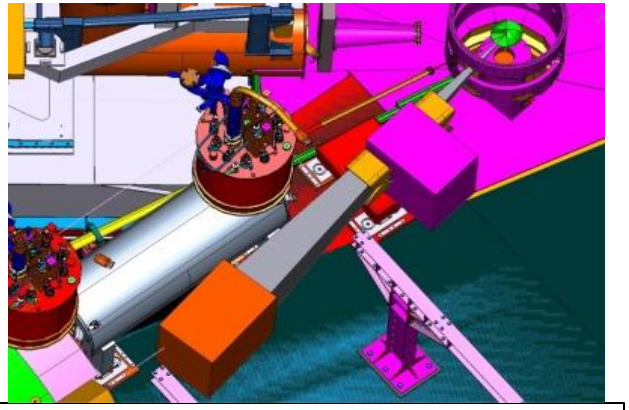
The damage to crystals is a limiting factor for beam current !



Expected dose rate versus angle

(Based on P. Degtiarenko's simulations.)



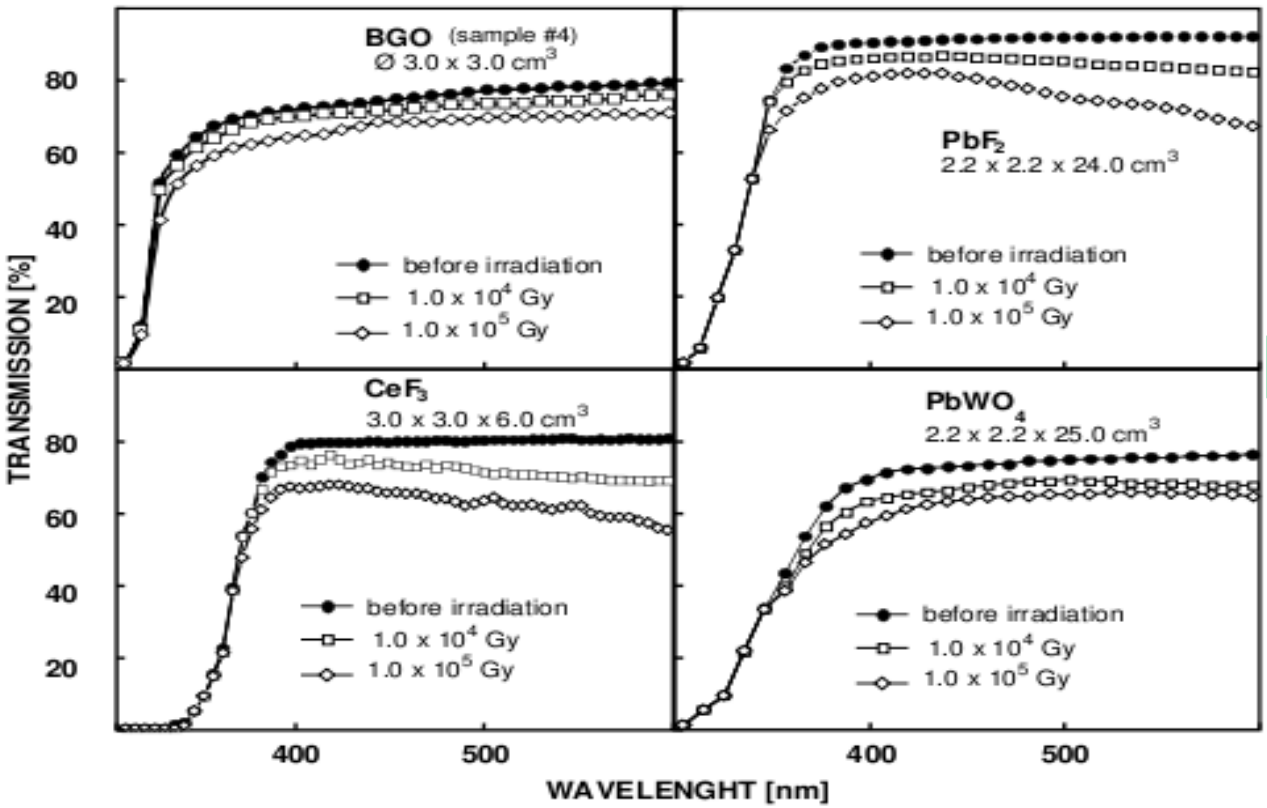


- **The radiation background is strongly angular (and energy) dependent.**
- **The magnet will sweep off most of the charged background below 300 MeV.**
- **Remaining low energy photon flux is capable to damage crystals (darkening, mostly in the first few cm).**

- **The detector will be operated in open geometry, prone to radiation damage.**
- **Curing of the crystals may be periodically needed in the course of the long running experiments.**

Radiation damage of heavy crystals

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



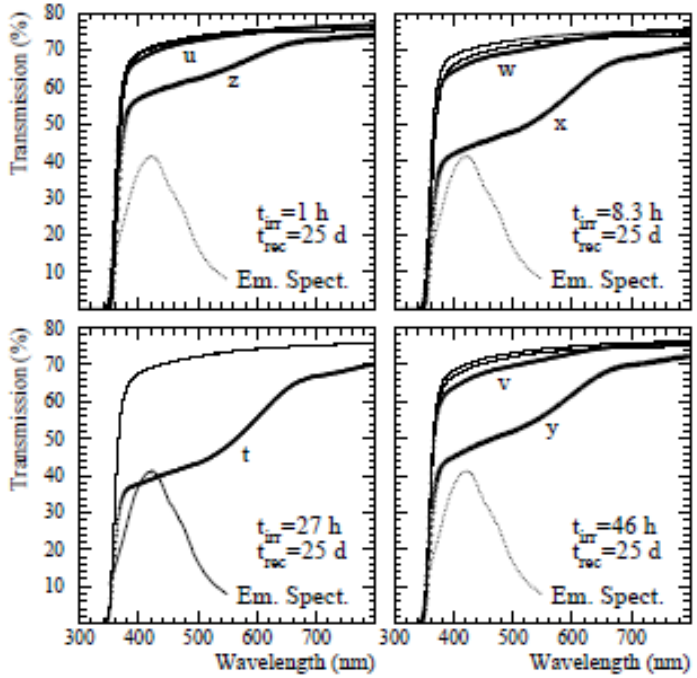
1 Gy = 100 rad

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

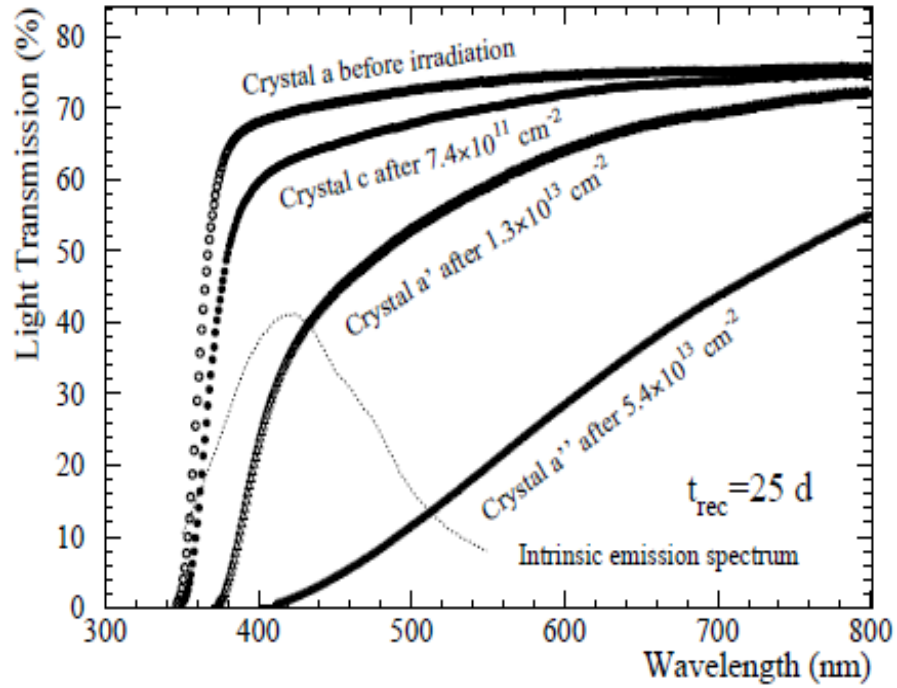
- Modest damage for nearly all crystals occurs at doses above ~10-20 krad.
- For integrated doses of 1-2 Mrad the radiation damage is significant.
- Radiation damage of the $PbWO_4$ and PbF_2 at doses below ~1 Mrad similar.

Photon & Proton induced damage in $PbWO_4$

Photon-irradiated



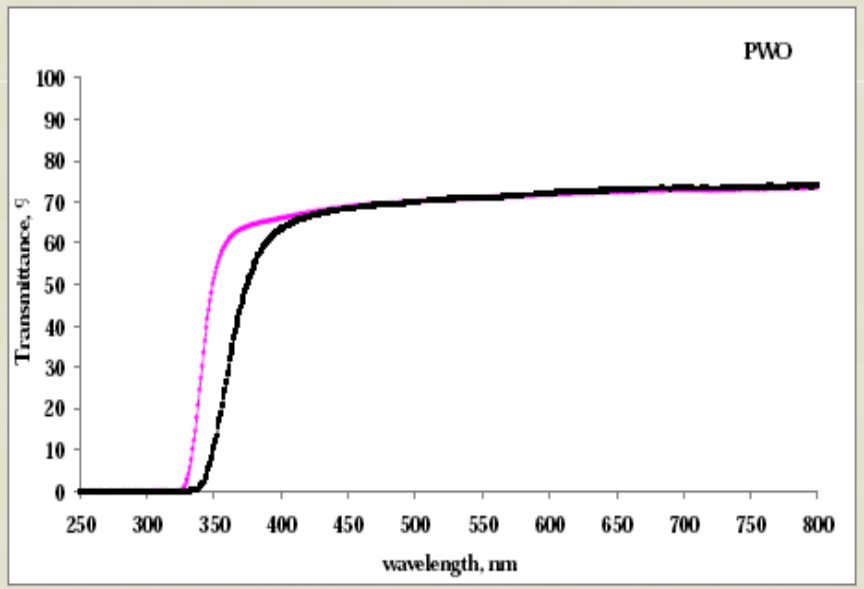
Proton-irradiated

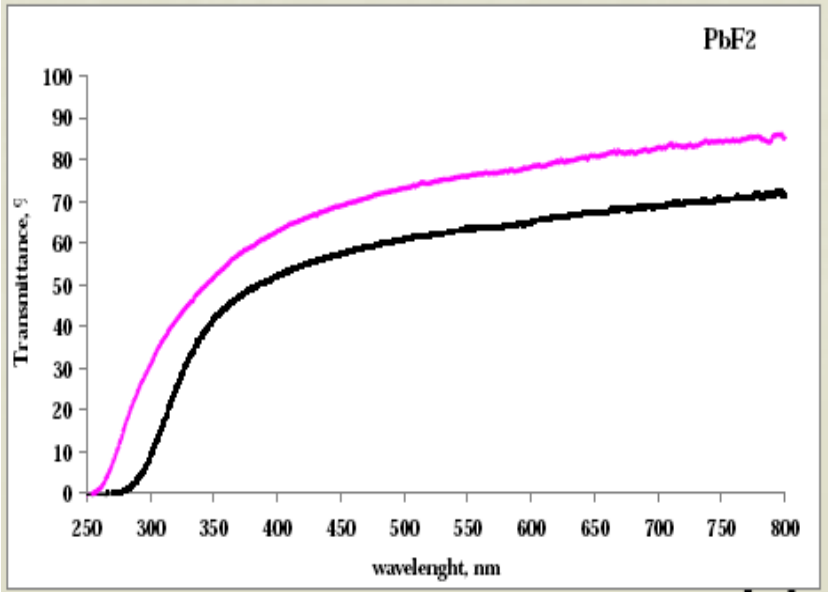


(From M. Huhtinen et al., ETHZ-IPP-PR-2004-03, Swiss Institute for Particle Physics)

- Degradation of the crystals 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.**

Proton induced radiation damage of $PbWO_4$ & PbF_2 crystals



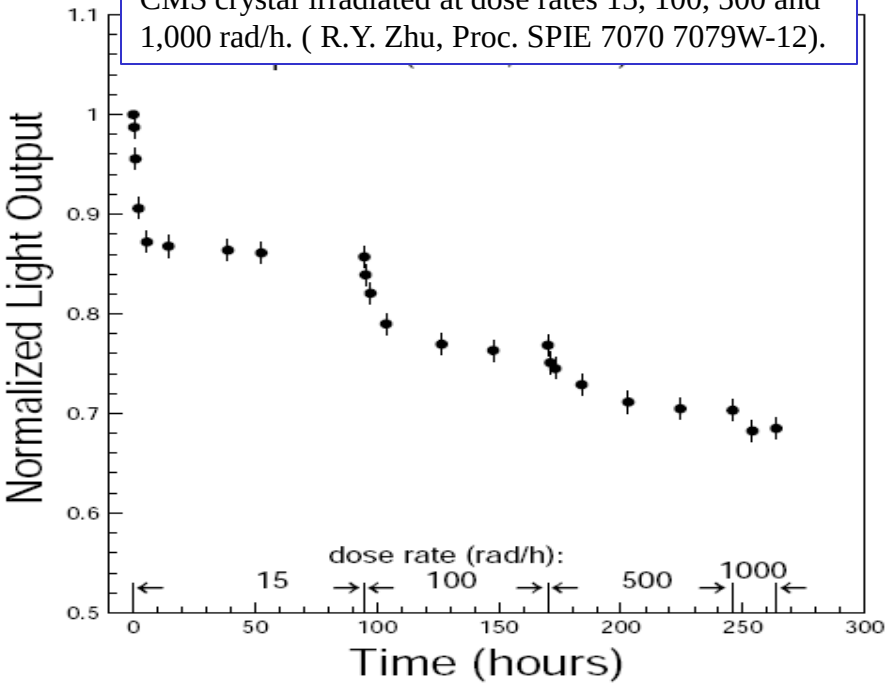


Transmission spectra of $PbWO_4$ and PbF_2 crystals before and after irradiation with 24 GeV protons (integral fluence 3×10^{13} p/cm^2). (From M. Korjik, CMS UW-FNAL-8.11.2011).

- Proton induces Radiation cause shift of the spectrum cutoff of $PbWO_4$ & PbF_2

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

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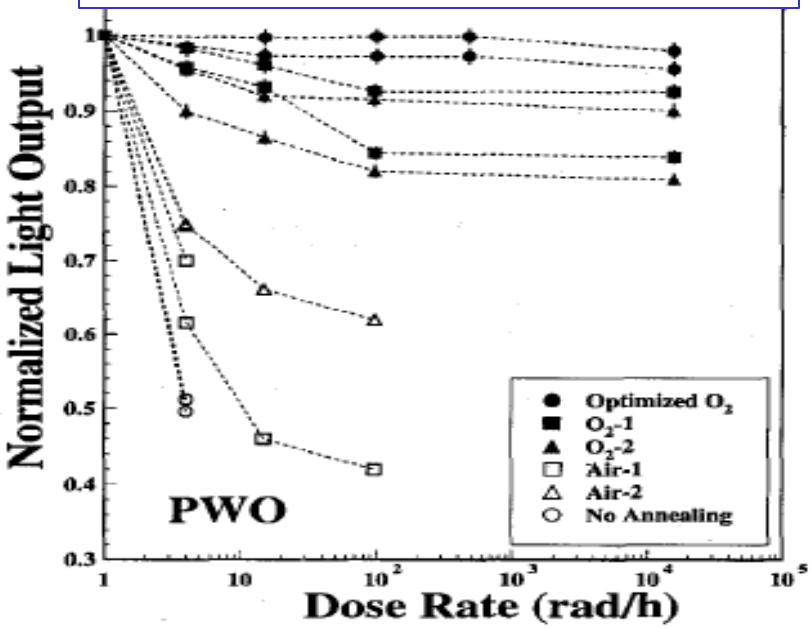
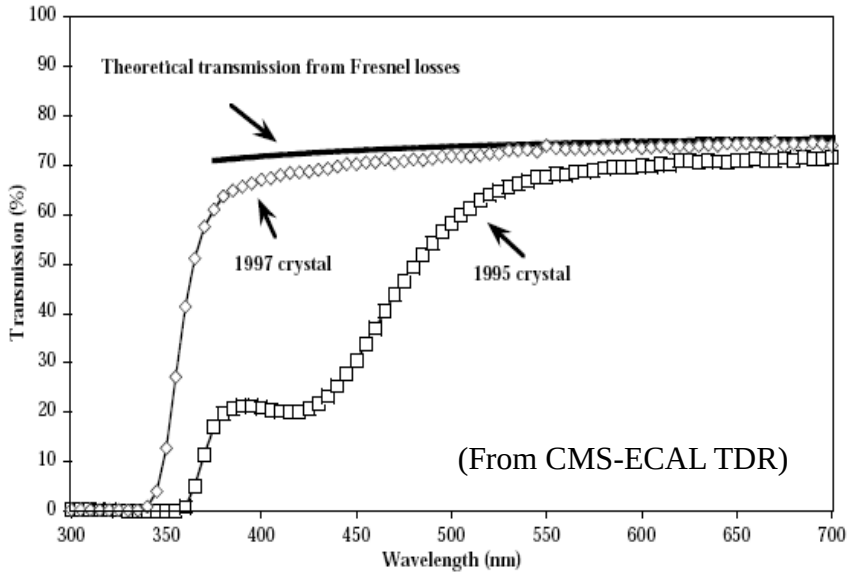
The samples prepared under different conditions. (R. Zhu et al., IEEE Trans.Nucl. Science, 45 (1998) 686



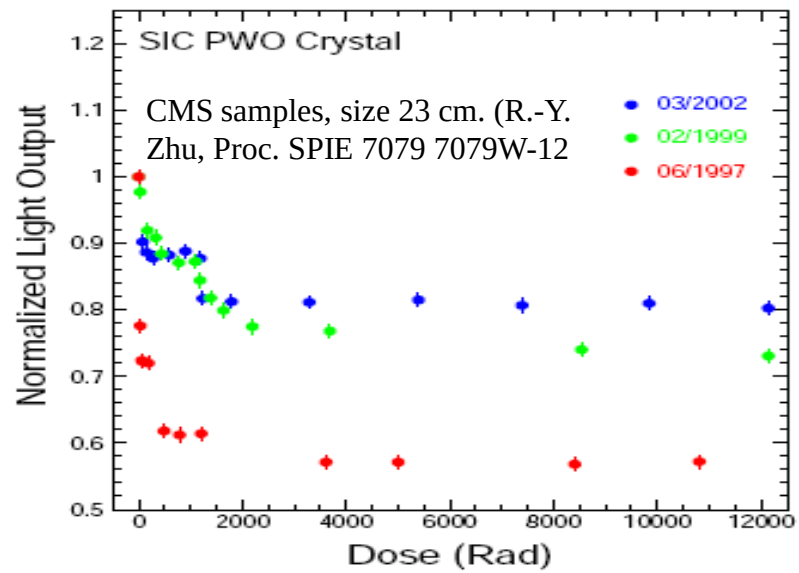
The normalized light output versus the dose rate

- **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.**

Progress in $PbWO_4$ optical quality and radiation hardness



Transmission for 23 cm-long $PbWO_4$ crystals produced in 1995 and 1997, compared to the maximum achievable



Normalized light output as a function of the dose

- The problem of old crystals was wide absorption near 370 & 420 nm which was resolved by using high purity materials, improving the crystal growing technology.
- The doping of a crystal with La, Lu, Gd, Nb and Y with a concentration of some tens of atomic ppm increases the radiation hardness.
- The latest crystals developed by BTCP and SIC for CMS and PANDA experiments have more light yield, better transmittance and increased radiation hardness.
- Trying to increase higher light yield always slows down the emission time !

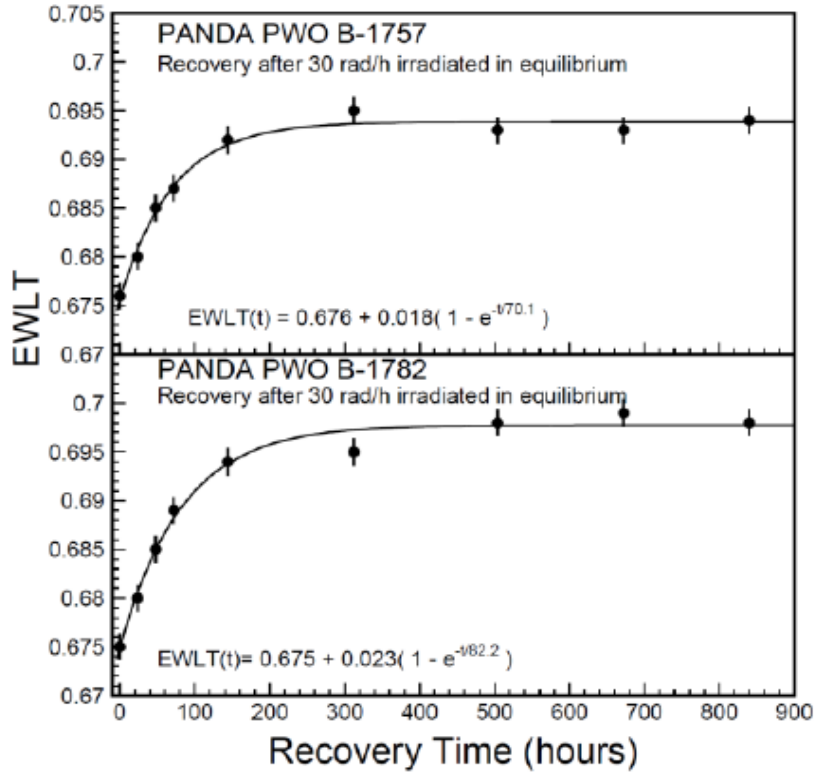
Spontaneous recovery of the crystals radiation damage

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)

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

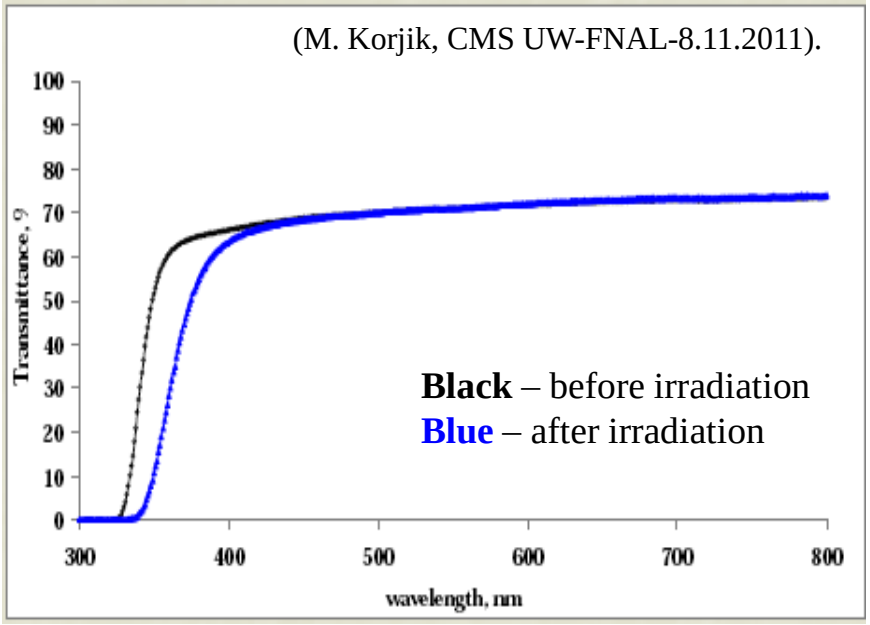


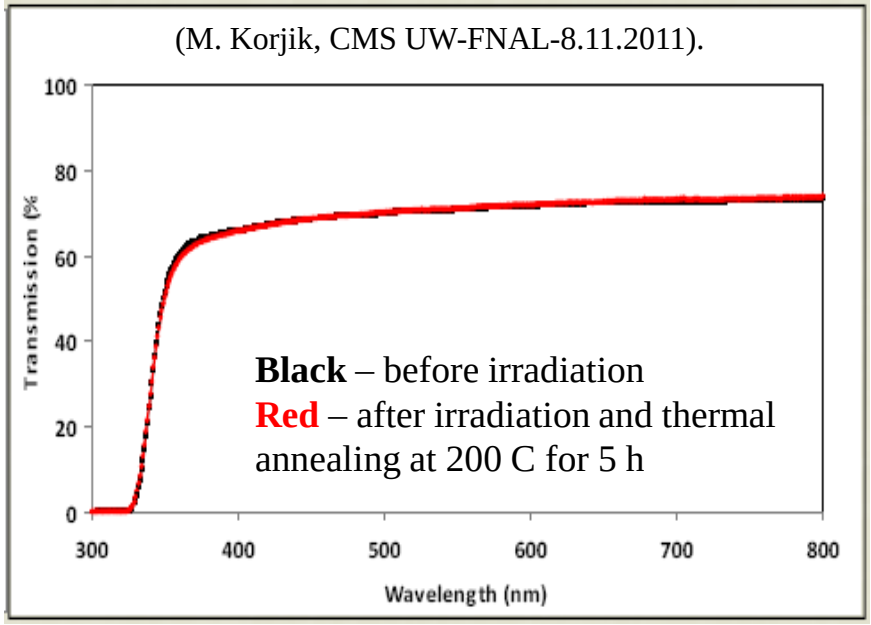
Recovery of the $PbWO_4$ emission weighted longitudinal transmittance

- **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 $PbWO_4$

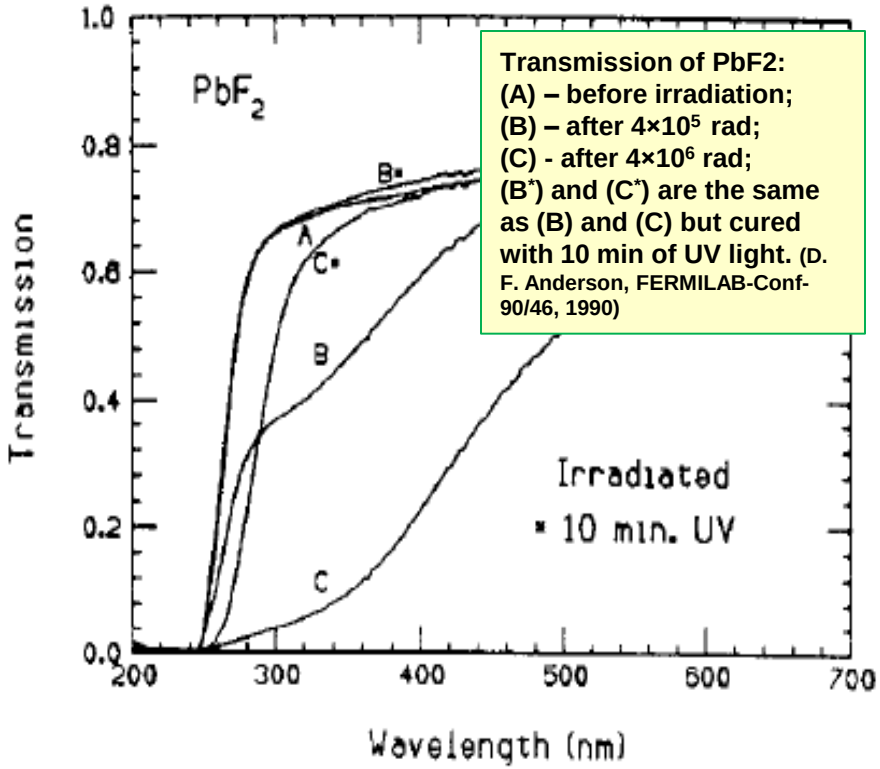
Radiation damage of $PbWO_4$ crystals by protons (integral fluence 3×10^{13} p/cm^2).





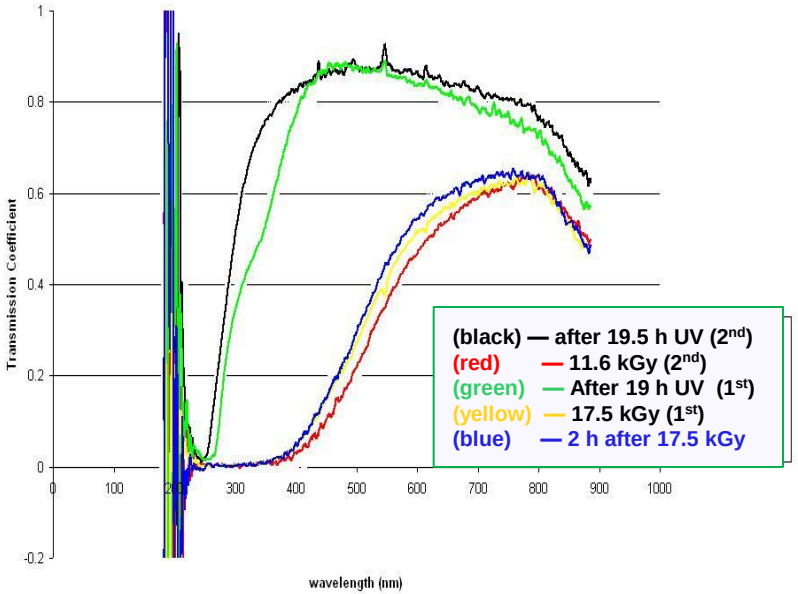
- **Full recovery of p-induced damage can by annealing at 200 °C.**
- **Thermal annealing very effective but it can not be performed in situ and will require full disassembling of the calorimeter.**
- **More practical and effective way of $PbWO_4$ *in-situ* curing is <u>optical bleaching.</u>**

Simulated UV-recovery radiation damage of PbF_2



Transmission of PbF2:
(A) – before irradiation;
(B) – after 4×10^5 rad;
(C) - after 4×10^6 rad;
(B^*) and (C^*) are the same as (B) and (C) but cured with 10 min of UV light. (D. F. Anderson, FERMILAB-Conf-90/46, 1990)

PbF2 calorimeter in Hall A experiment
(A. Comsonne, Workshop Calor-2008)



- **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.**

Approaches to remove degradation of NPS calorimeter

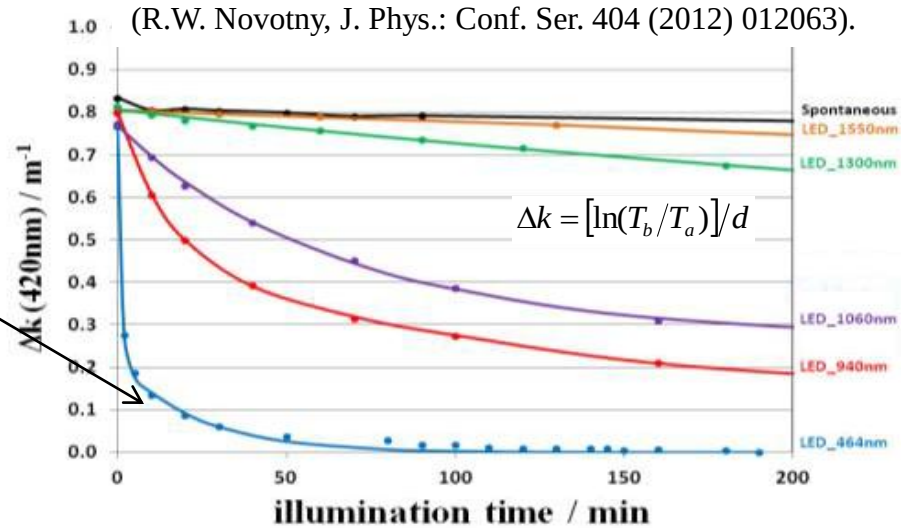
Effective way of $PbWO_4$ *in-situ* curing is <u>optical bleaching.</u>

Two approaches we are considering:

A) <u>Standard curing</u> at light λ~300-700 nm

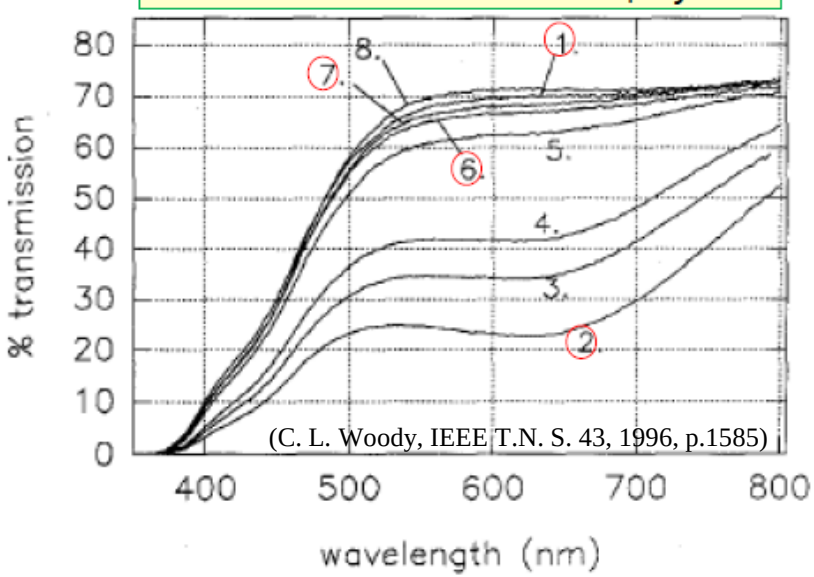
- Requires PMTs off and hall access, removing front panel & installing the curing system
- Curing strongly depends on the light wavelength, thus fast curing can be done with blue light
- 2 shifts needed (recovery time ~10-15 hours)
- Curing needed once per 2-3 weeks (~50 krad dose accumulation at rates <100 -150 rad/h)

(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



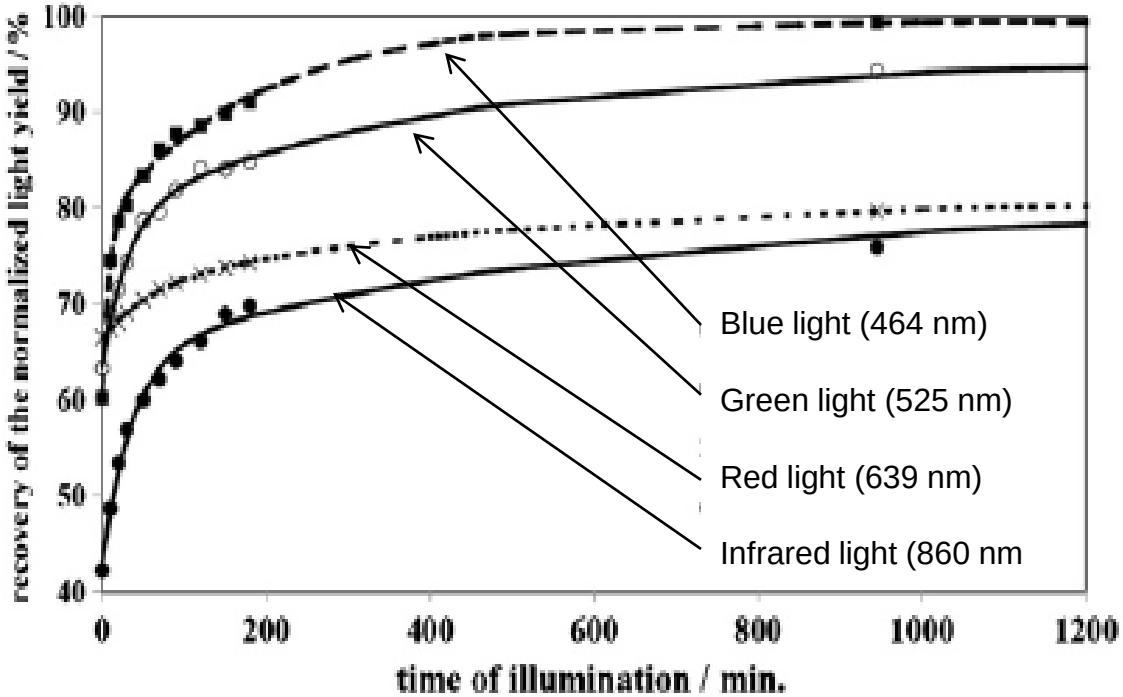
(1)- before radiation,
(2)- after a dose of 834 krad,
(3)- after 5 h of bleaching at 700 nm,
(4)- after 12 h at 700 nm,
(5)- after 5 h at 600 nm (5),
(6)- after 10 h at 600 nm,
(7)- after 7 h at 640 nm,
(8)- after 2 h of annealing (200 °C).

Simulated recovery of the $PbWO_4$ with IR light

B) Recovery with visible and IR light

- Works very well for low doses (~3 krad)
- Can be operated remotely, no hall access

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

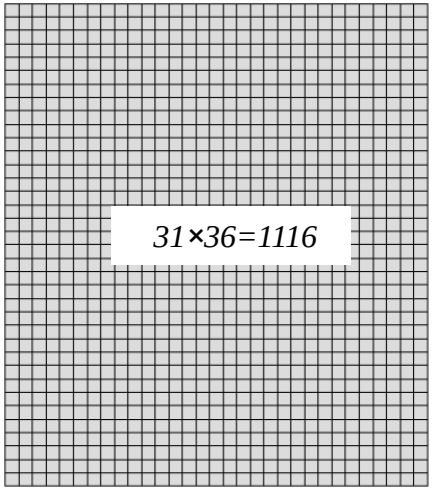


IR stimulated recovery of 3 krad radiation induced normalized LO of PbWO crystal .

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

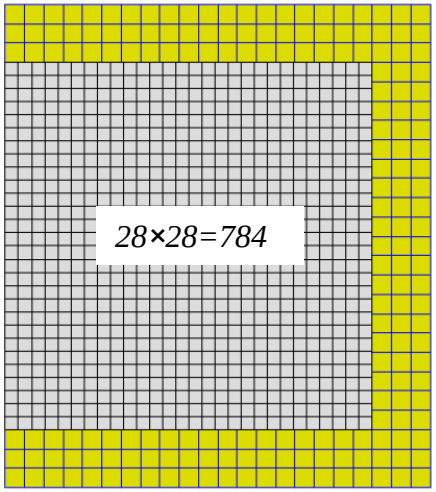
Possible options for the calorimeter

64×74 cm²



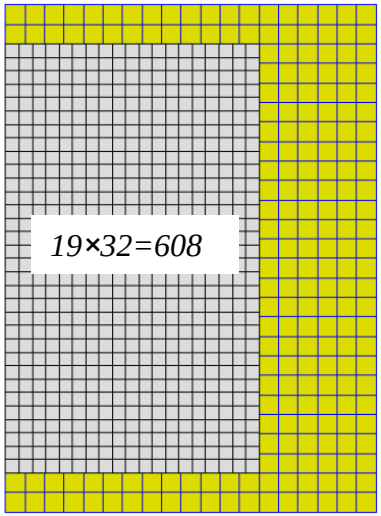
All block are $PbWO_4$

57×75 cm²



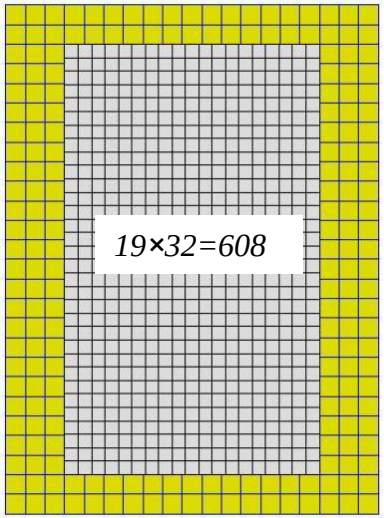
784 $PbWO_4$ + *189* PbF_2

57×78 cm²



608 $PbWO_4$ + *208* PbF_2

57×78 cm²



608 $PbWO_4$ + *208* PbF_2

$PbWO_4$ blocks dimensions: 2.05×2.05 cm²
PbF_2 blocks dimensions: 3.0×3.0 cm²

(Figures from S. Zhamkochyan)

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

Manufactures of $PbWO_4$ and PbF_2 crystals

Company	Part	Quantity	Price/block	Estimated to ship
Marke-Tech International, www.mkt-intl.com colleen@mktintl.com	PbWO codoped with La and Y at level of <400 ppm	1 3 5 or more	2,495 1,560 1,245	~18 weeks
Shanghai Institute of Ceramics, Chinese Academy of Science (SICCAS); fang.jun@siccas.com	PbWO doped	10-12 ~1,000	~1,500 ~1,200	24 months
Kinheng Int. Hold. Co. (Shanghai, China); ivan@kinheng-crystal.com	PbWO doped	1 or more	~2,950	
Crytur (Czech Republic) houzvika@crytur.cz	PbWO doped	10-12 >100	~3,300 ~3,000	

Furukawa (Japan) and Beijing Glass Research Institute (BGRI, China) also are producers of heavy crystals. But no any contact and information about price and quality of the crystals.

How about annealing and reuse crystals from CMS or ATLAS ?

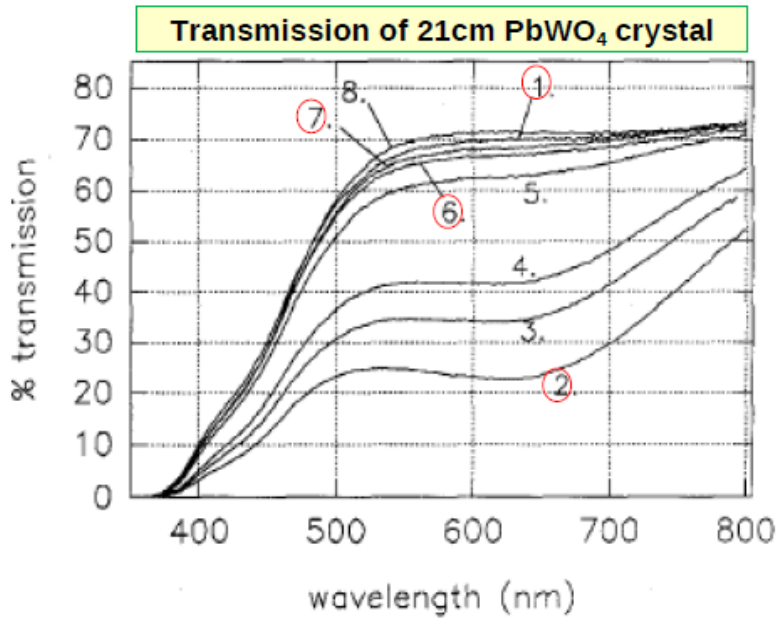
Quality requirements of PbWO4 blocks

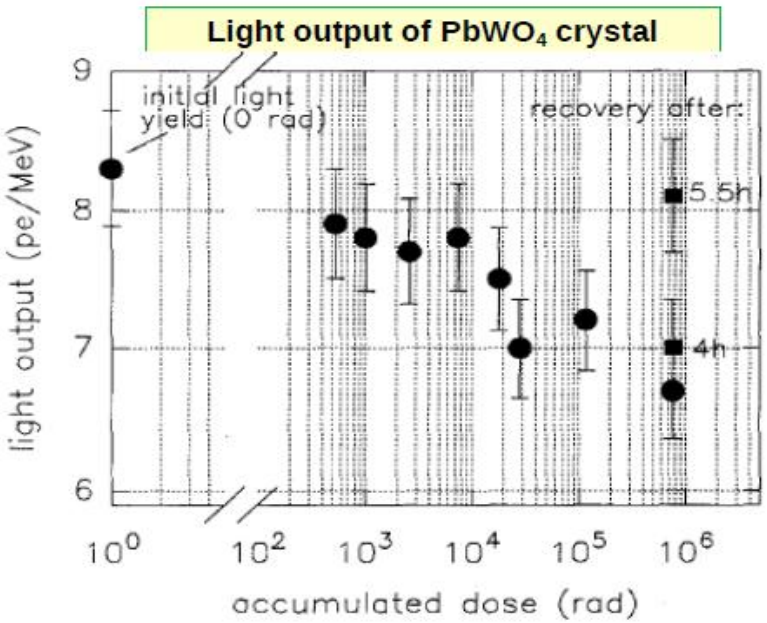
Parameter	Proposed	Acceptable	CMS requirements
Tolerance in dimensions (μm)	±50	±100	<30
Light yield (pe/MeV)	5-6	3-4	>8
Transmission (%) At λ~420nm	50-60	~40	>55
Uniformity in optical properties between crystals (%)	~10	~15-20	<10
Radiation hardness LY loss (%) for 1.5 Krad at dose rate 15rad/h	5	~10	<6
Uniformity rad. Degradation between crystals at the same dose (%)	~20	<30	~10
Uniformity light yield temp. dependence slope (%)	-	-	~5-10

Thank You !

Simulated recovery of the $PbWO_4$ with UV light

A fast and effective way of $PbWO_4$ *in-situ* curing is optical bleaching.





Transmission of 21cm $PbWO_4$

(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 thermal annealing (200° C).

(C. L. Woody et al., IEEE Trans. N. S. 43, 1996, p.1585).

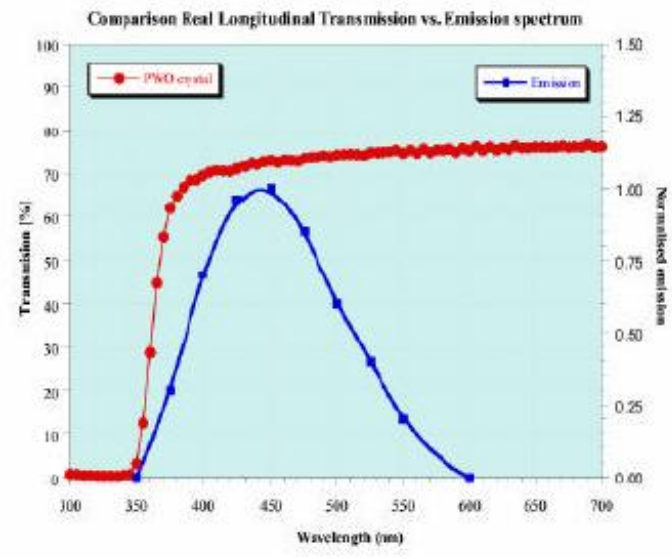
Two approaches are considered:

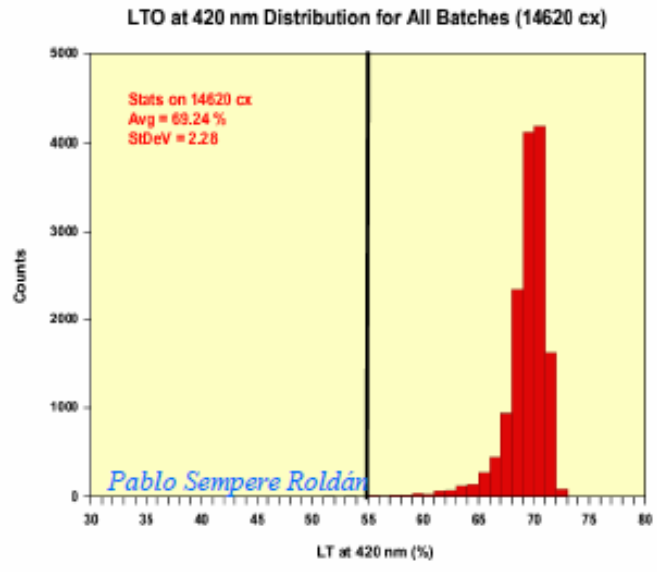
A) Standard curing at 500-700 nm wavelengths

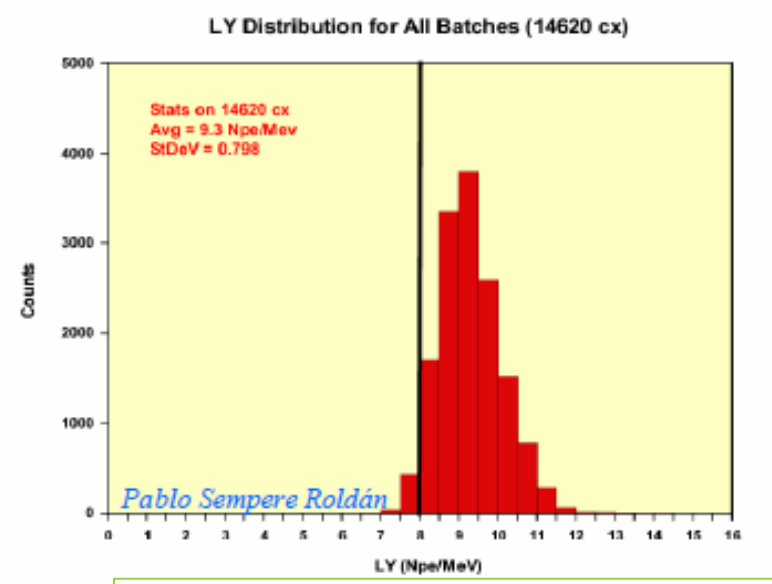
- Requires hall access, removing front panel & installing the curing system
- 2 shifts needed (recovery time ~10-15 hours)
- Once per 2-3 weeks (50 krad dose accumulation at rates <100 -150 rad/h

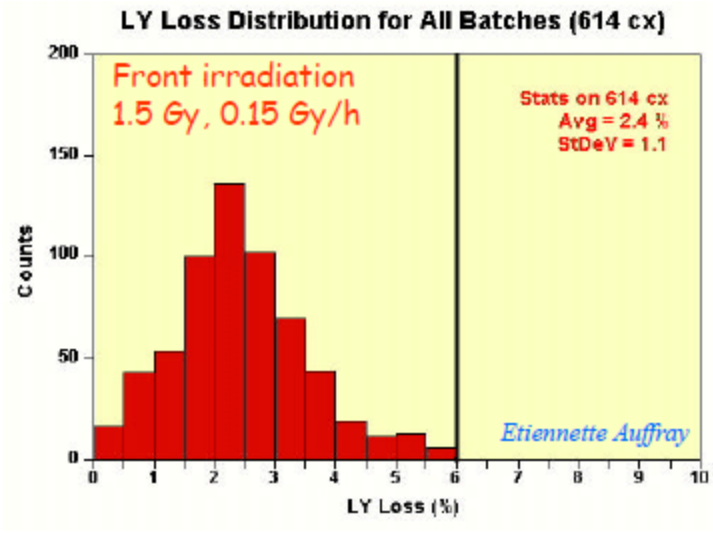
with Sweep Magnet ON)

Selection BTCP (Russia) Crystals for CMS



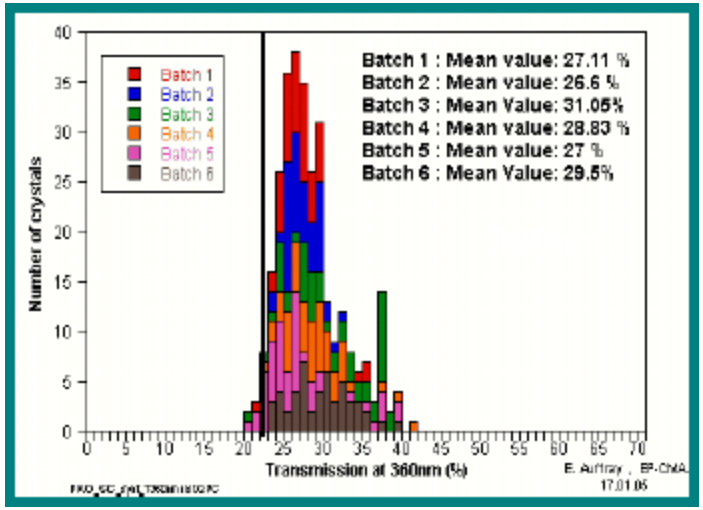


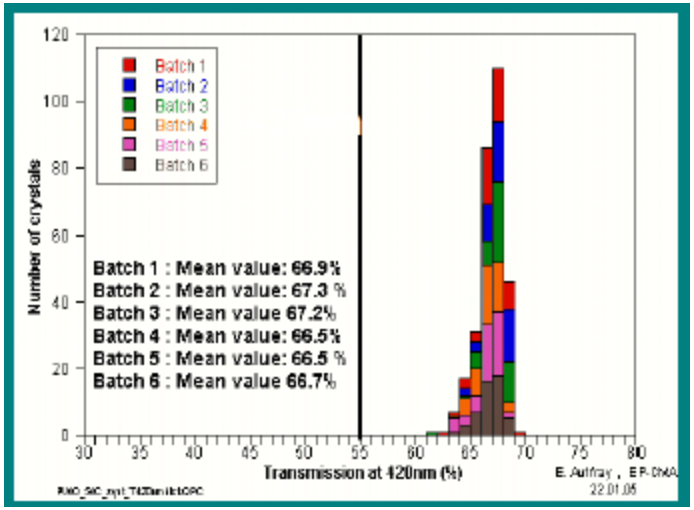


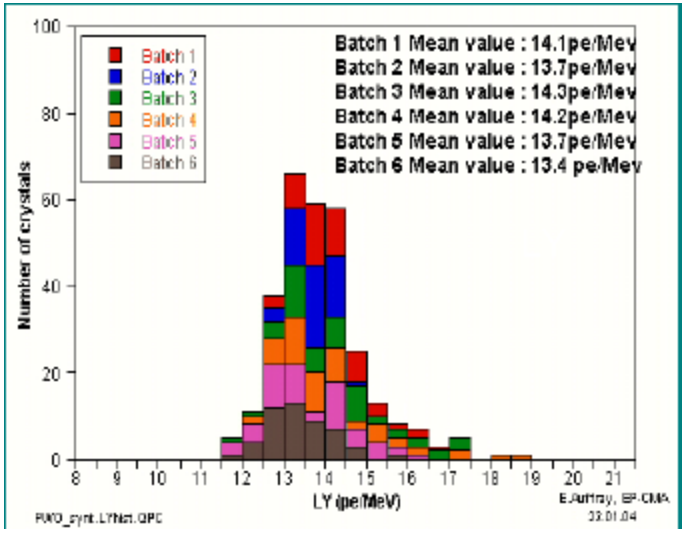


(From Jean Fay presentation, COLOR-2004 workshop)

Selection of SIC (China) Crystals for CMS



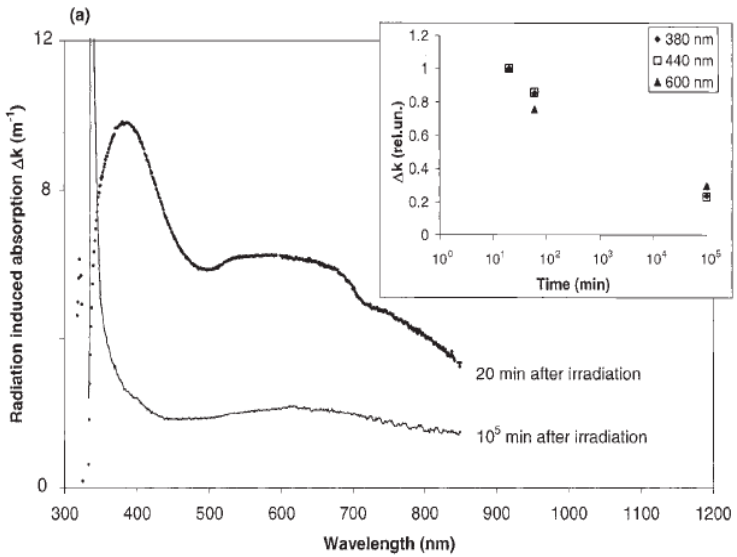


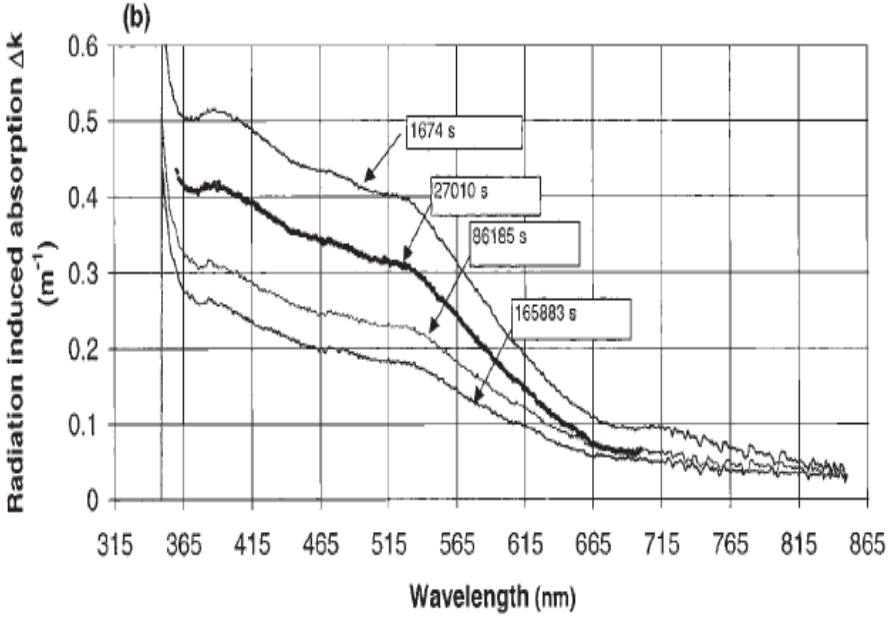


(From F. Cavalarri presentation, CMS Collaboration)

Progress in $PbWO_4$ development (I)

The doping of a crystal with La, Lu, Gd, Nb and Y with a concentration of some tens of atomic ppm increases the radiation hardness



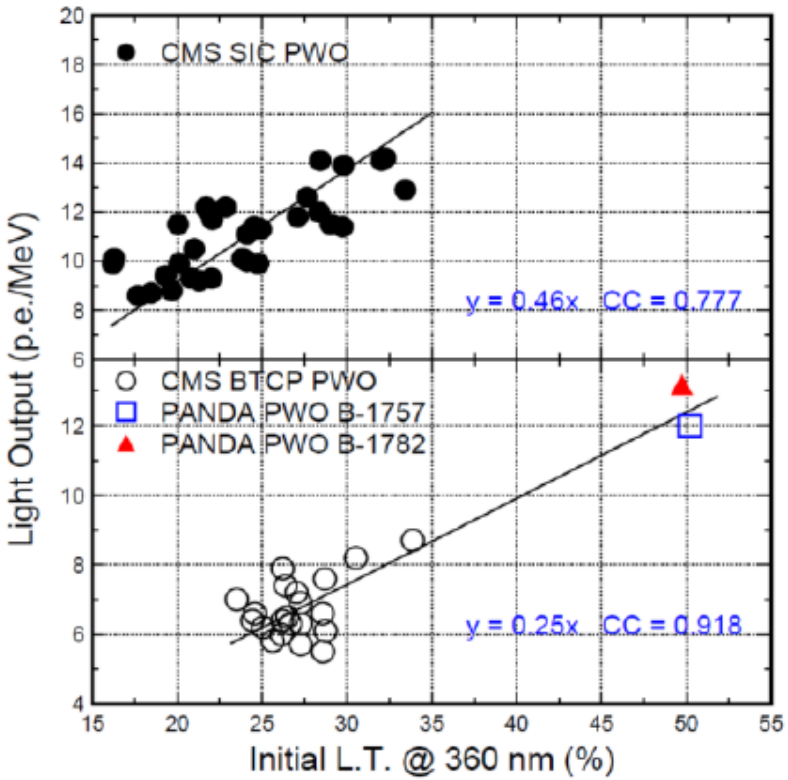


Spectra of induced absorption of PbWO crystals measured at room temperature:
(a) - undoped crystal in 20 and 10^5 min after radiation;
(b) - regular mass produced doped crystal at different times.
(From A. N. Annenkov et al., Phys. Stat. Sol. 191 (2002) 277).

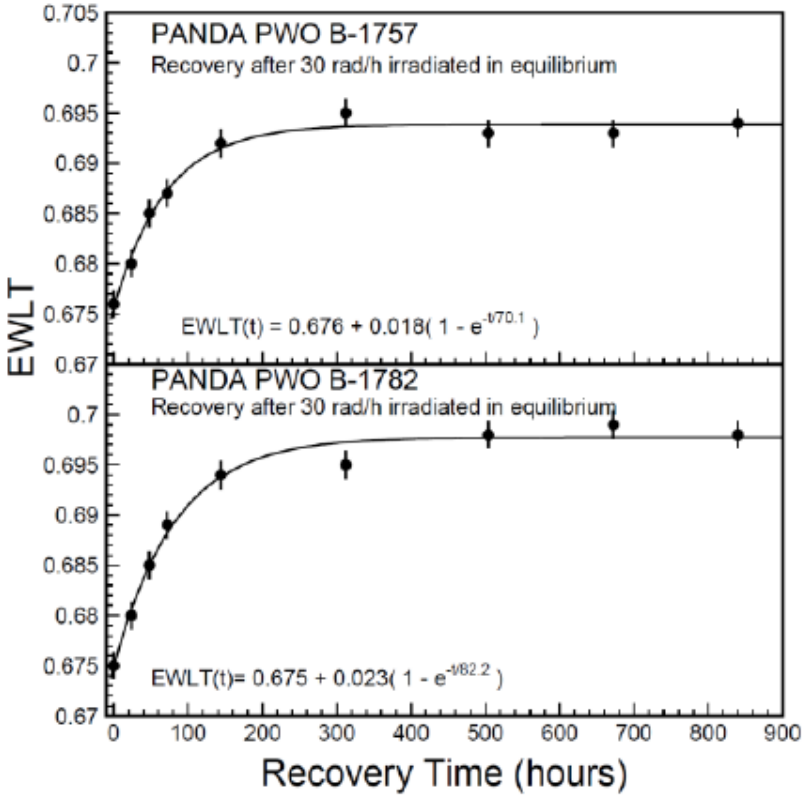
Trying to increase higher light yield always slows down the emission time !

Progress in $PbWO_4$ development (II)

The latest crystals developed by BTCP and SIC for CMS and PANDA experiments have more light yield and better transmittance.



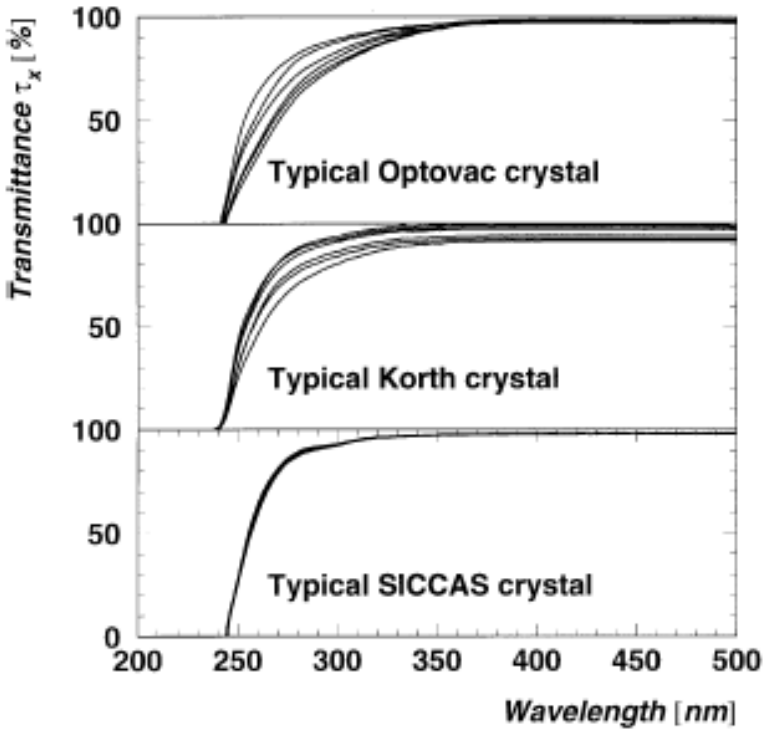
Correlation between the initial LO and initial LT for the $PbWO_4$. (R.-Y. Zhu, J. of Phys.: Conf. Ser. 404 (2012) 012025).



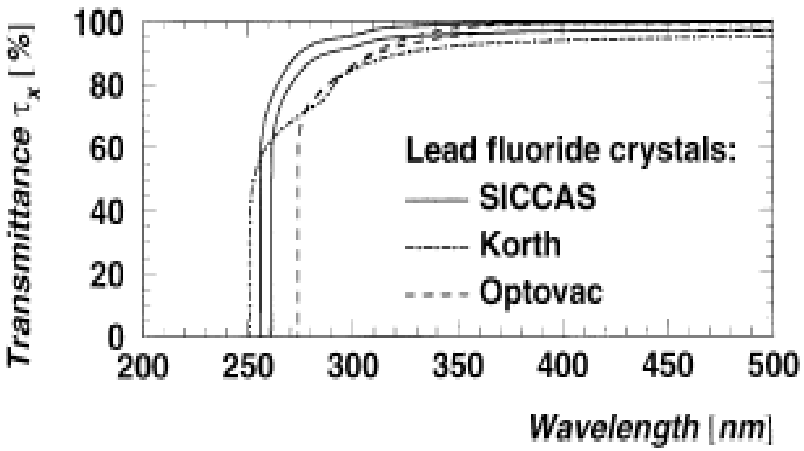
Recovery of the $PbWO_4$ EWLT as irradiated at 30 rad/h. (R.-Y. Zhu, J. of Phys.: Conf. Ser. 404 (2012) 012025).

Progress in PbF_2 development

The PbF_2 crystals developed by SICCAS have better transmittance and homogeneity.



Homogeneity of PbF_2 crystals. The initial transmittance perpendicular to the longitudinal axis at six position is shown for crystals from three different manufacturers. (From P. Achenbach et al., NIM A416, 1998, p.357)

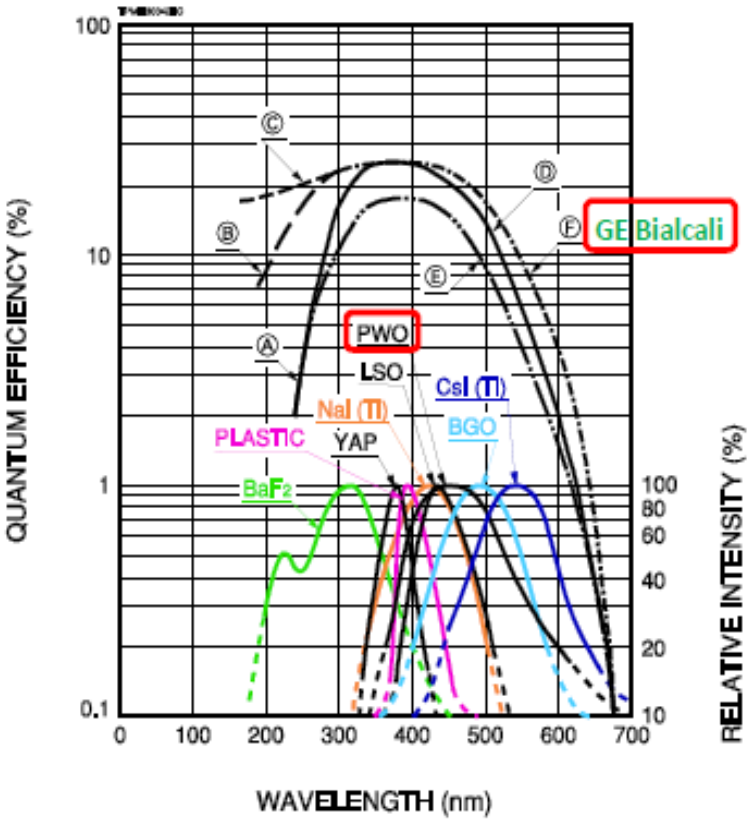


A comparison of the longitudinal transmittance for PbF_2 crystals from three different manufacturers. (From P. Achenbach et al., NIM A416, 1998, p.357)

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

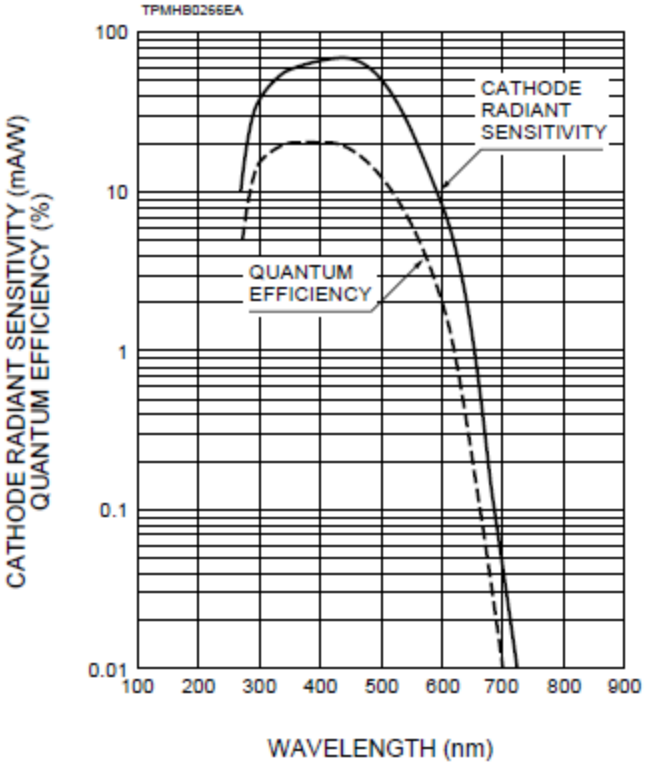


Sensitivity range of R4125 matches range of emission of $PbWO_4$

Choice of PMT for PbF_2

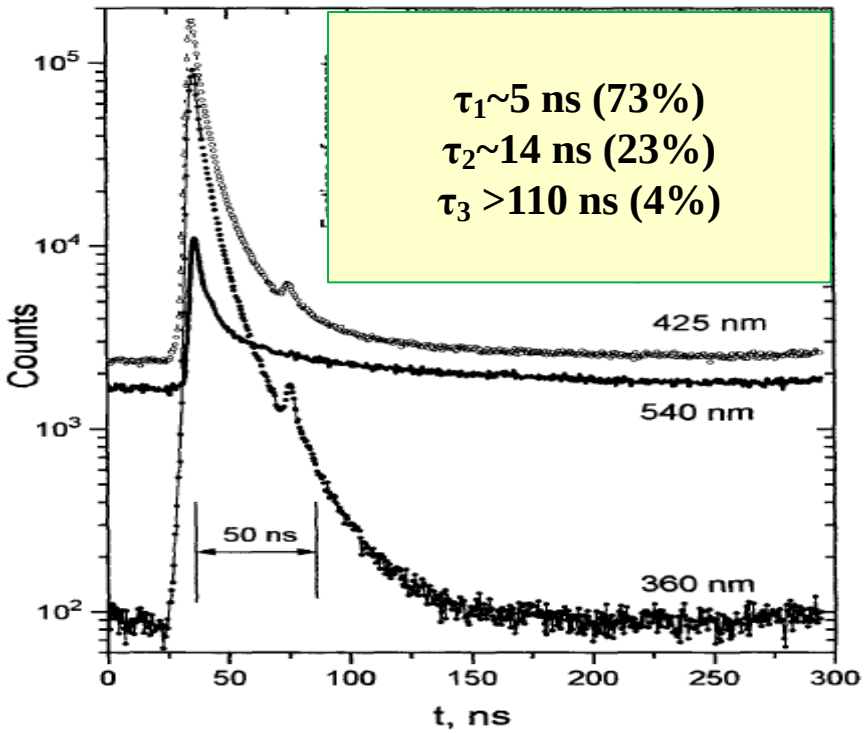
Hamamatsu R7700 PMT (used in Hall A).

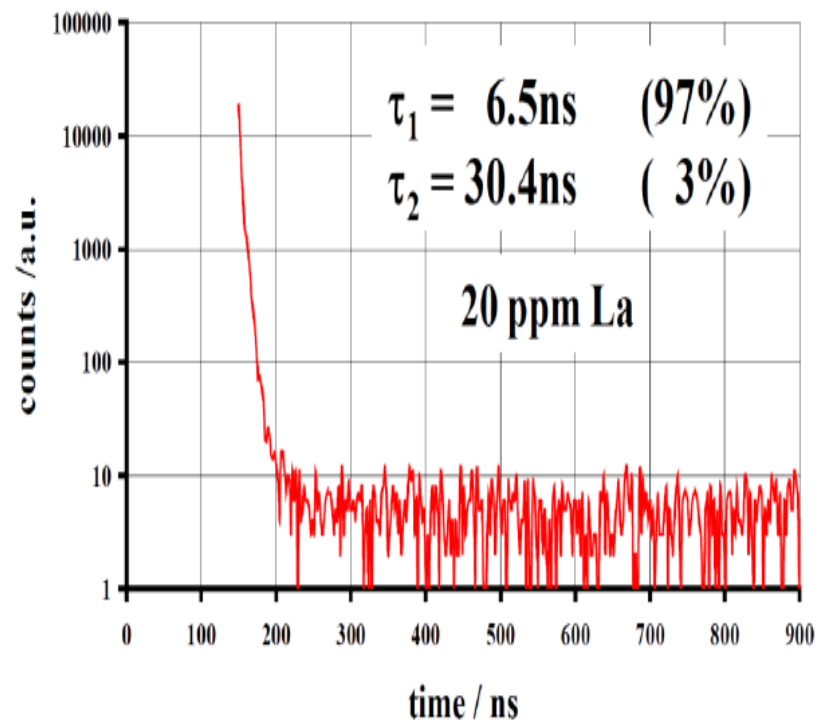
Parameter	Value
Effective area	22 mm×22mm
No. of stages	8
Photocathode	Bialkali
Sensitivity range	300 – 650 nm
QE max at ~400nm	20 %
Supply voltage	900 V
Gain	10^4
Dark Current	~2.0 nA
Rise Time	1.2 ns
Transit Time	< 1 ns



Sensitivity range of R7700 matches range of emission of PbF_2

Decay time for the emission of $PbWO_4$

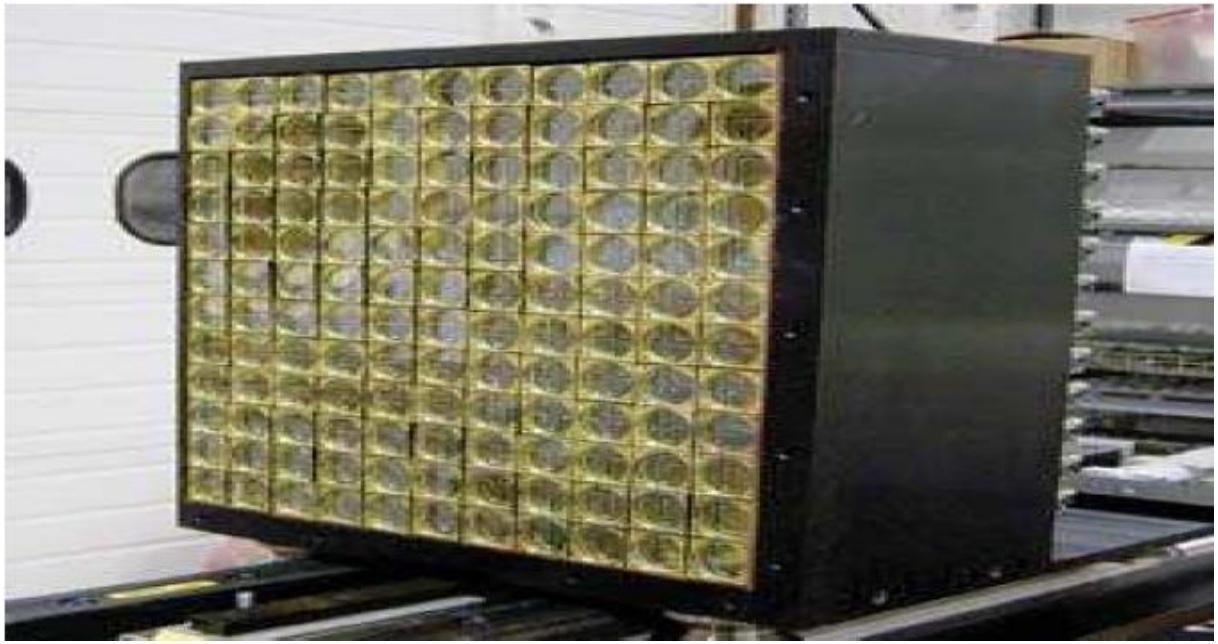




The emission of $PbWO_4$ includes three components:
τ_1 ~5ns (73%), has values 0.6, 1.8, 2.3 11.9 ns;
τ_2 ~14 ns (23%) has 3.44, 5.16, 20.54, 60.6 ns;
τ_3 >110 ns (~4% of the total intensity).
(A. N. Belsky et al., Chem. Phys. Lett. 243 (1995) 552)

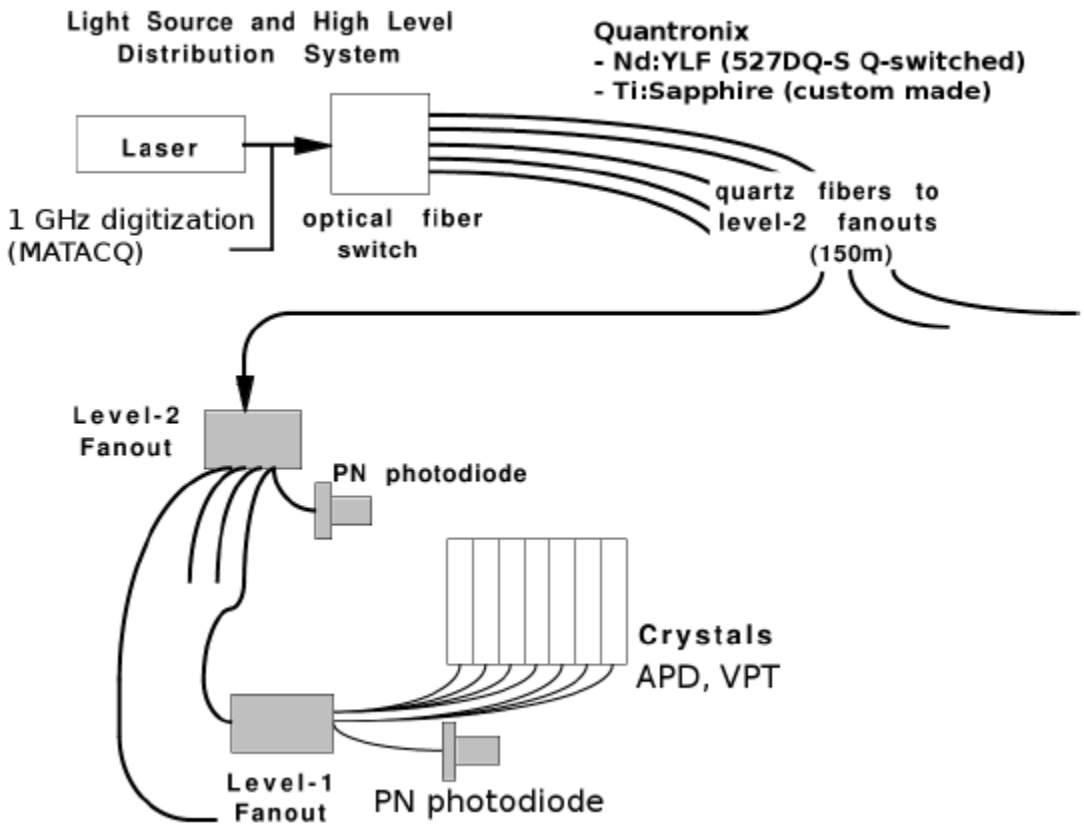
New $PbWO_4$ crystals for PANDA includes two emission components:
τ_1 ~6.5 ns (97%);
τ_2 ~30.4 ns (3% of the total intensity).
(R. W. Novotny, IEEE, NSS, 2003)

PbF_2 calorimeter in Hall A DVCS experiment



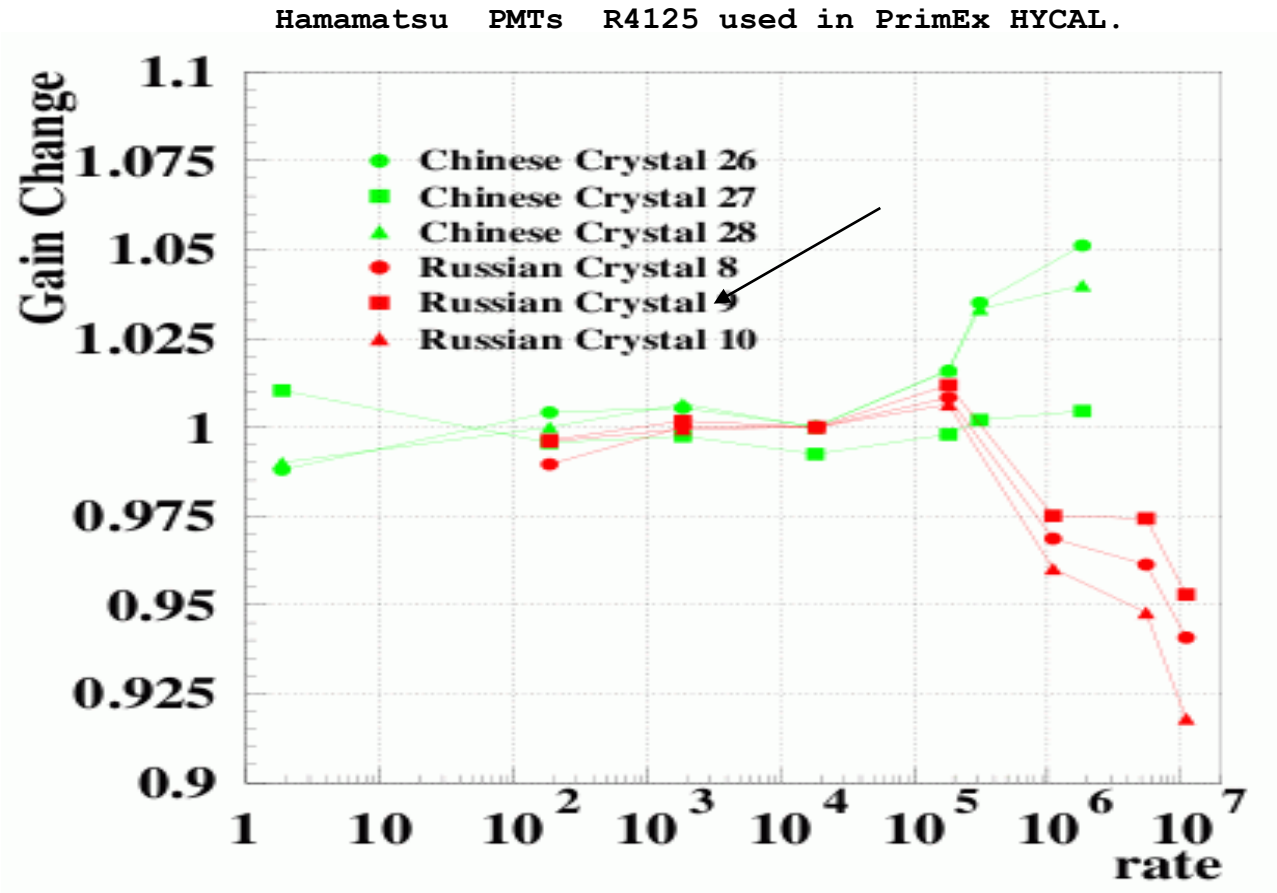
Visual inspection of PbF_2 blocks after Hall A first DVCS experiment. The darkness of some blocks on the target side (very evident for block 39) most likely is created by low energy electrons and photons. (From S. Gregoire report, August 16, 2007).

Gain Monitoring System



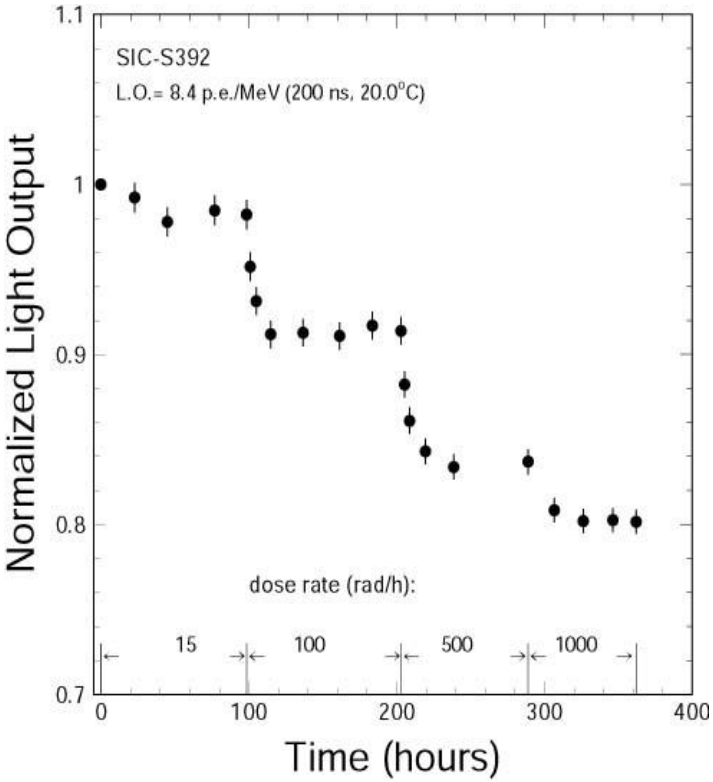
The CMS laser monitoring system. 1 GHz sampled laser beam, 2 level distribution systems, PN photodiodes as reference monitors (F. Ferri, J. of Phys.: Conf. Ser. 404 (2012) 012041, CALOR2012).

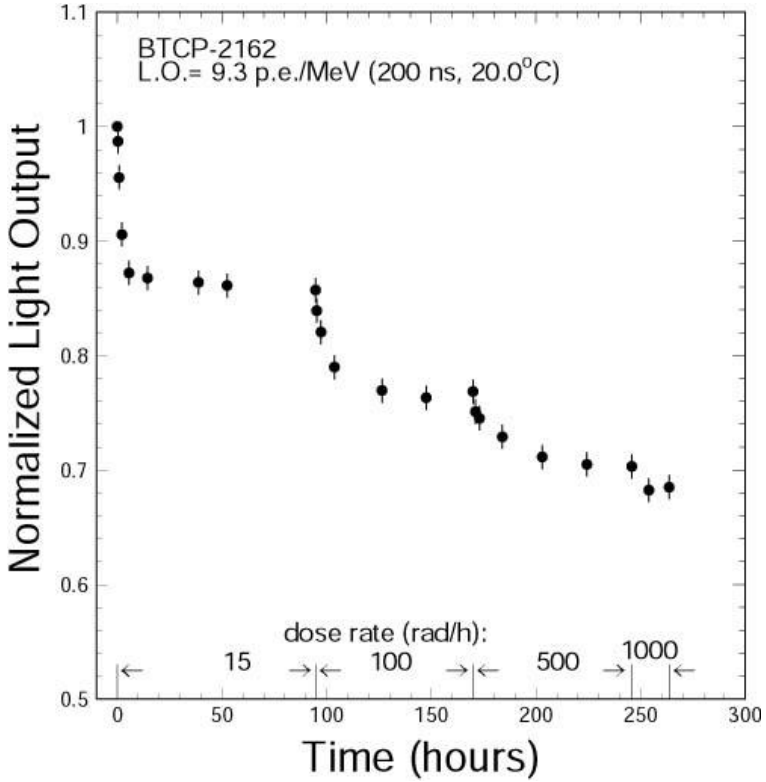
The PMT gain variation with rate



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

CMS PWO(Y): Radiation Damage





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