Neutral Particle Spectrometer

(Some technical aspects)

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Requirements of the experiments

Parameter	DVCS (unpol. LH2)	DVCS (pol. 3He)	WACS	DES π^0	SIDIS π^0
Photon angl. res. (mrad)			1–2	0.5 – 0.75	0.5 – 0. 75
Energy res. (%)	$(5 – 6)/\sqrt{E}$		~5	$(2 – 3)/\sqrt{E}$	$(2 – 3)/\sqrt{E}$
Distance from target	1.5 – 3.0			4.0	4.0
Sweeping magnet (Tm)	0.3	0.3	0.3	0.3	0.3
Second arm spectr.	HMS	HMS	HMS	HMS	HMS
Photon angl. (degrees)	12.4 – 23.0		33 – 69	10.1—23.4	16.3—19.2
Photon energies (GeV)	2.7 — 7.6		1.1– 3.4	3.1—5.7	0.5—5.7
Luminosity ($cm^{-2}cm^{-1}$)	$\sim10^{38}$	$\sim10^{37}$	$\sim10^{39}$	$\sim3\times10^{37}$	$\sim3\times10^{37}$
Acceptance	~10 msr			60%/25 msr	10—60%/25 msr
Beam current (μA)	2.5 — 25	~ 60	~ 40, +6%Cu	1—2 (*)	1—2 (*)
Targets	LH2	30 cm 3He	15 cm LH2	10 cm LH2	10 cm LH2
Beam time (hours)	~2000		~1000	894	604

(*) 1-2 μA is a minimum requirement and background dependent. If background acceptable, then will use higher currents!

- 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

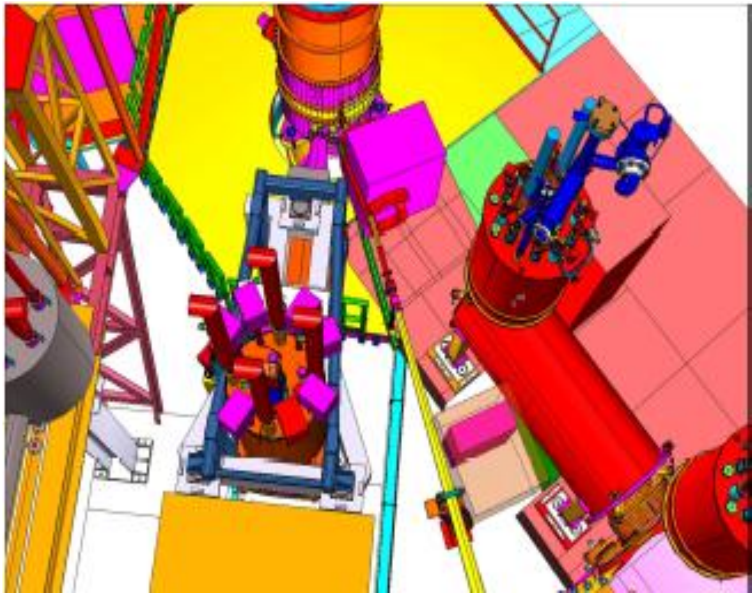
Neutral Particle Detector Options with crystals

Two options: $PbWO_4$ or PbF_2

Material	PbWO4	PbF2
Dimensions (cm)	64×74	13×16
Crystal size (cm)	2.05×2.05×18.0	3.0×3.0×18.0
Number of crystals	1116	208
Distance from target (m)	4.0	1.5-3
Position resolution (mm)	2—3	2—3
Solid angle/crystal (mrad)	0.044 (dist. 3 m) 0.025 (dist. 4 m)	0.9 (dist. 1 m) 0.1 (dist. 3 m)
Energy resolution (σ_E/E, %)	2.3/√E	5.3/√E
Timing resolution , σ(ns)		0.6—1.0
Radiation hardness (Gy)	10^4 –10^5 (*)	10^4 --10^5

(*) At extremely high dose rate of ~100krad/h and accumulated dose ~2.5 Mrad the light output of PbWO4 reduces by a factor ~3 (V. A. Batarin et al., Nucl. Phys. B 150, 2006, pp. 262-266).

The π^0 detector in Hall C



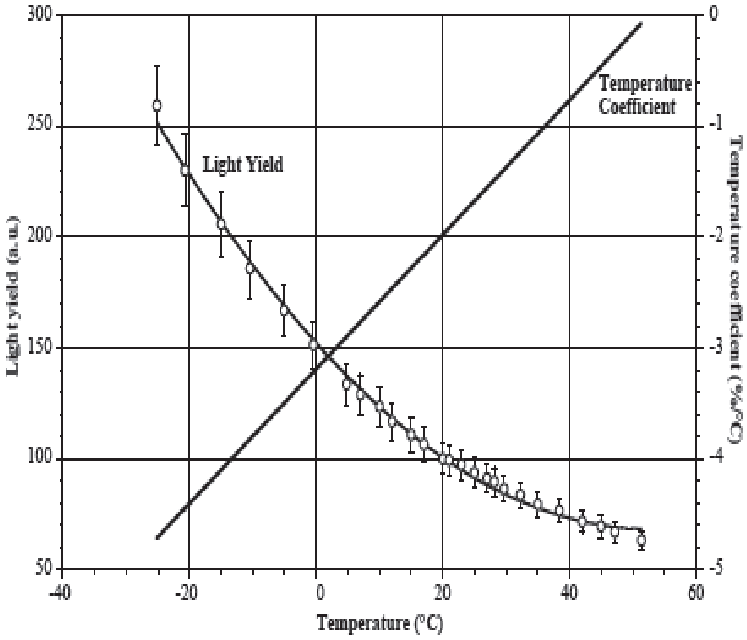
The cylinder at the top centre is the vacuum Chamber containing the 10 cm LH2 target. The long yellow tube emanating from the scattering chamber on the lower right is the downstream beam pipe. To the left of the beam pipe is the HMS. To the right of the beam pipe is the SHMS which will be used for π^0 experiment as a carriage to support the detector and the sweep magnet.

Properties of $PbWO_4$ and PbF_2 crystals

Parameter	Lead Tungsten ($PbWO_4$)	Lead Fluoride (PbF_2)	
Density (g/cm3)	8.28	7.66-7.77	
Radiation length Xo (cm)	0.89	0.93-0.95	
Refraction index	2.36 (λ = 420 nm) 2.24 (λ = 600 nm)	1.8-2.0 (depending on λ)	
Transmission range (nm)	340-1000	250 -- 1100	
Moliere radius (cm)	2.19	2.22	
Radiation type Sensitivity to low en. bckgr.	Scintillation (~13% Čerenkov) Sensitive	Pure Čerenkov Insensitive (no scintillation)	!
Timing property (slow/fast) τ_{sc}, ns (%)	≈30 ns / 10 ns 5 (73%) 14 (23%) 110 (4%)	Very fast, Total pulse width < 20 ns	!
Lead content (% by weight)	> 85	85	
Hydroscopicity	No	No	
Energy resolution σ_E/E (%)	~2.4/$\sqrt{E}$	5.3/$\sqrt{E}$	!
Position resolution σ (mm)	~2.5/$\sqrt{E}$	~1.5/$\sqrt{E}$	
Photon yields per 1 MeV	~140-200	~1.0-2.0	
Temperature dependence of Light Yield	~ -2%/^{o}C at room temperature	No need of temperature stabilization	!
Critical Energy (MeV)	--	8.6--9.0	

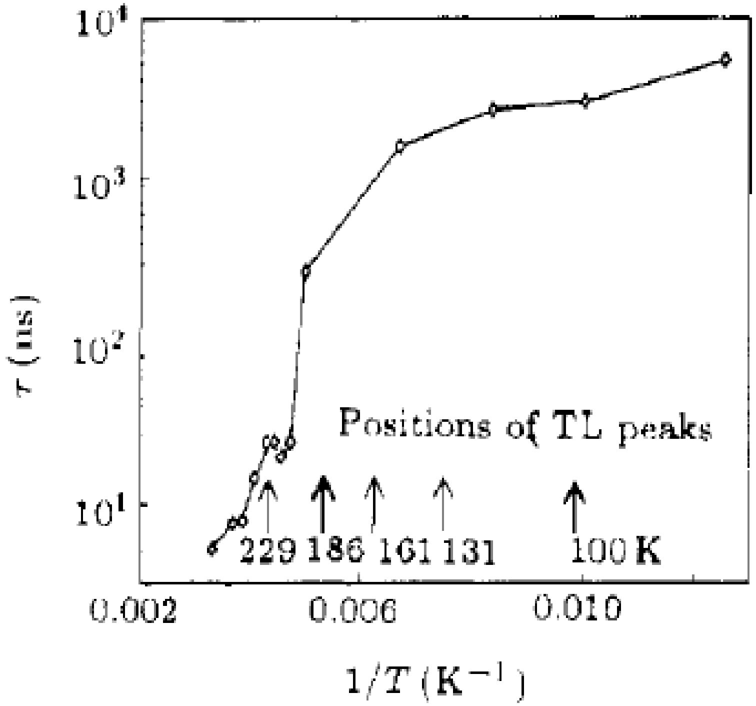
Temperature dependence of $PbWO_4$

Light yield



Temperature dependence of the light yield and temperature coefficient of the PbWO4 crystal (P. Leqcoq et al., NIM A 365, p. 291, 1994)

Decay time



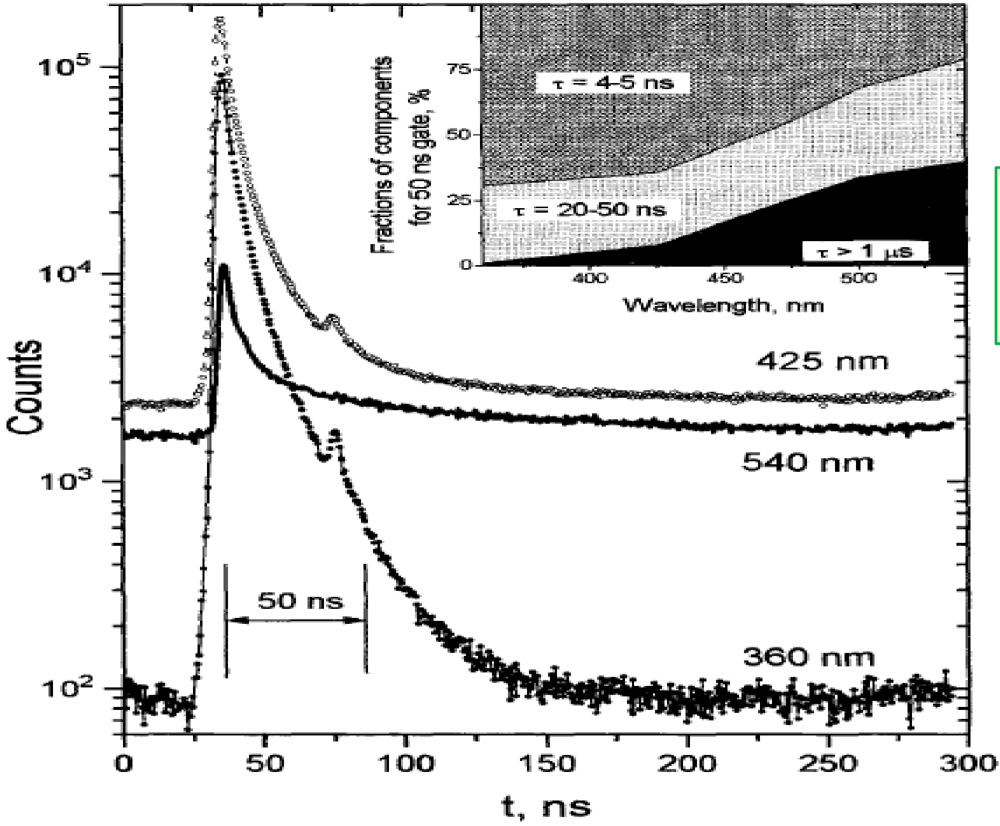
Temperature dependence of the decay time of the emission of the λ=430 nm from PbWO4 crystal. (Shi Chao-Shu, Chin. Phys. Lett. 15, p.55, 1998)

- The light yield increases at low temperature, but with increasing the luminescence decay time and decreasing radiation resistance of the $PbWO_4$ crystal.
  (N. R. Krutyak et al., J. Appl. Spectr. 79, p.211, 2012)

- Need Temperature controlled frame !

Decay time for the emission of $PbWO_4$

The emission of $PbWO_4$ includes one to three components, and increases with increasing wavelength: τ_1 has values 0.6, 1.8, 2.3 11.9 ns; and τ_2 has 3.44, 5.16, 20.54, 60.6 ns for emission of 400, 430, 500, 550 nm respectively.
A lifetime τ_3 of microsecond order, but it only several % of the total intensity.

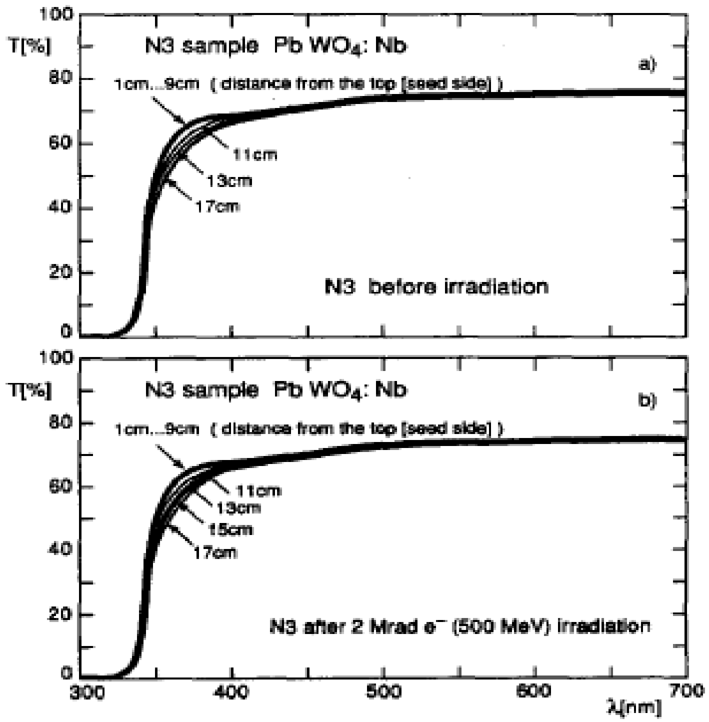


τ_1~5 ns (73%)
τ_2~14 ns (23%)
τ_3 >110 ns (4%)

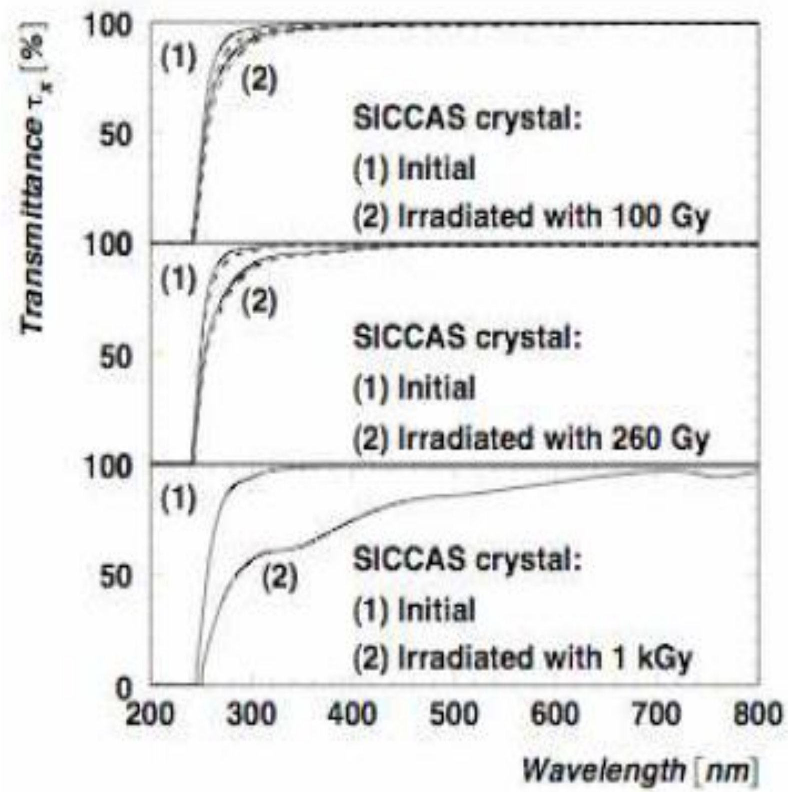
Spectral dependence of the fraction of decay components of $PbWO_4$ after X-ray the excitation pulse is shown in the inset. (A. N. Belsky et al., Chem. Phys. Lett. 243 (1995) 552)

Radiation hardness of $PbWO_4$ and PbF_2 crystals

$PbWO_4$



Transmission of $PbWO_4$:
(a) Initial and (b) after 2 Mrad dose.



PbF_2

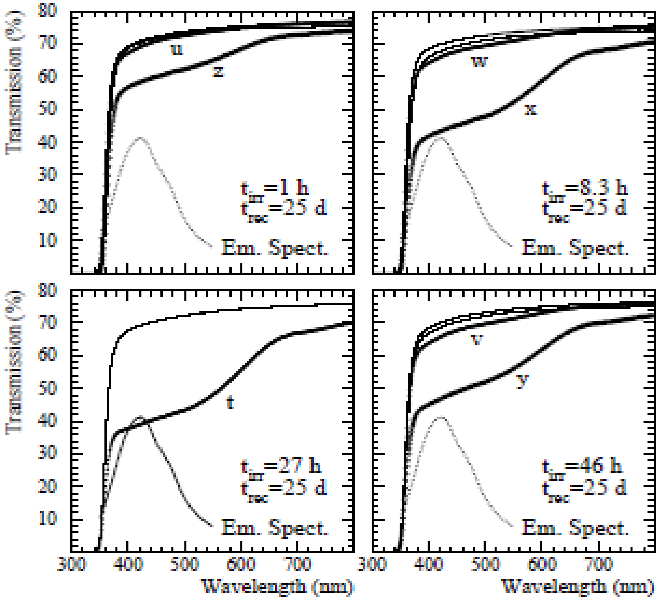
The high dose effect on PbF_2 blocks.

(A. Fyodorov et al., Rad. Meas. 26, 107, 1996); P. Achenbach et al., NIM, A 290, 385, 1990).

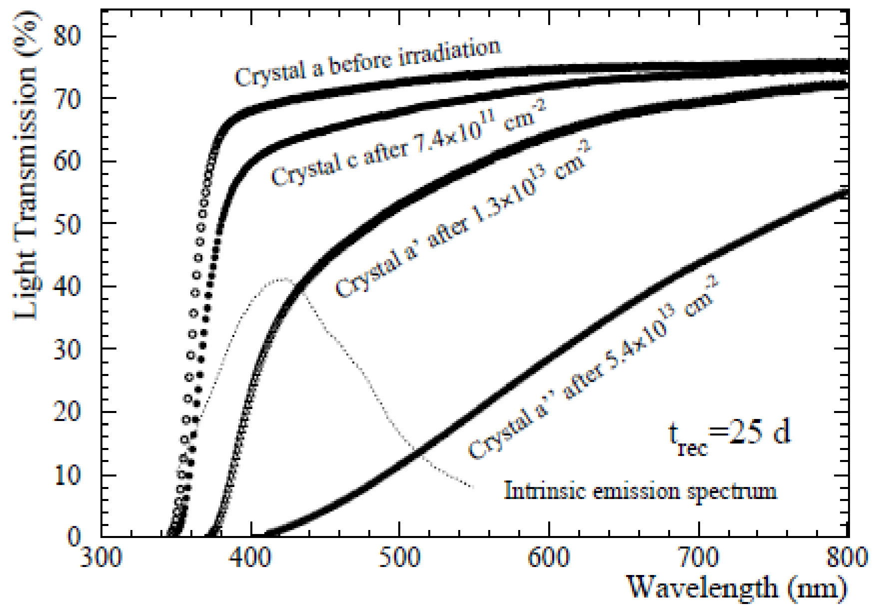
- PbF_2: modest damage at ~30 krad and damage is significant at doses > 100krad. Recovery by a few days after the radiation. (P. Kozma et al., NIM, 149, 2002). 1Gy = 1J/kg =100rad
- To improve the radiation resistance, the crystals are doped with a small amount (~100 ppm) of Nb, La, Lu, Y, Gd or Al

Photon & Proton induced damage in $PbWO_4$

Photon-irradiated

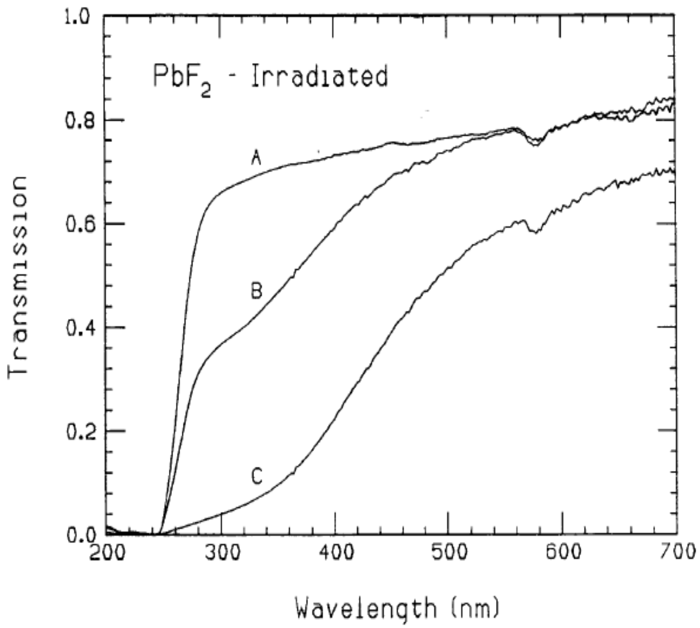


Proton-irradiated

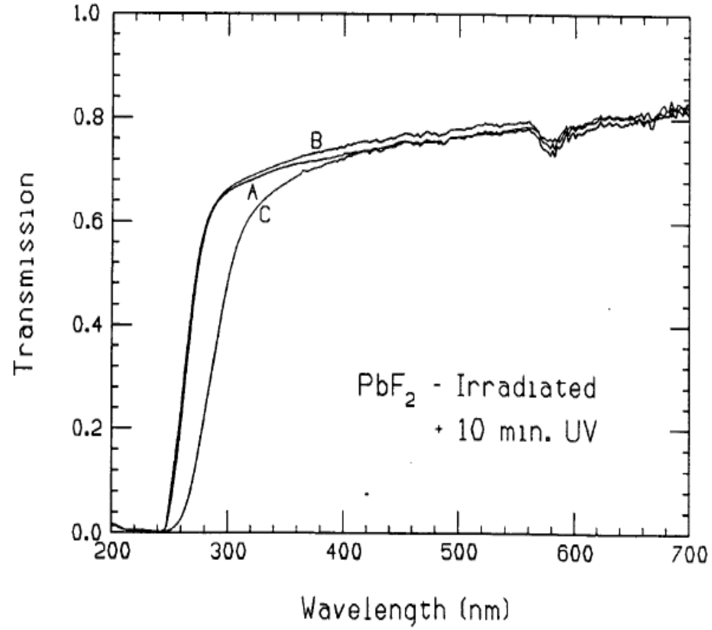


- **At doses >1 kGy (>100 krad) clear differences in the Light Transmission characteristics of the crystals exposed protons and those exposed to photons have been observed.**
  (M. Huhtinen et al., ETHZ-IPP-PR-2004-03, Swiss Institute for Particle Physics)
- **In proton-irradiated crystals, the band-edge shifts towards longer wavelengths, while band-edge remains stable in the γ-irradiated crystals.**
- **The photon induced damage saturates after a few hours of exposure at dose rate 1 kG/h (100 krad/h), while proton induced damage increases linearly with fluence.**
- **The creation of nuclear fragments during hadron irradiation causes the crystals to become radioactive.**

Radiation damage of PbF_2 (and UV recovery)



Transmission of PbF_2: (A) before irradiation, and (B) after 4×10^5 rad and (C) after 4×10^6 rad.



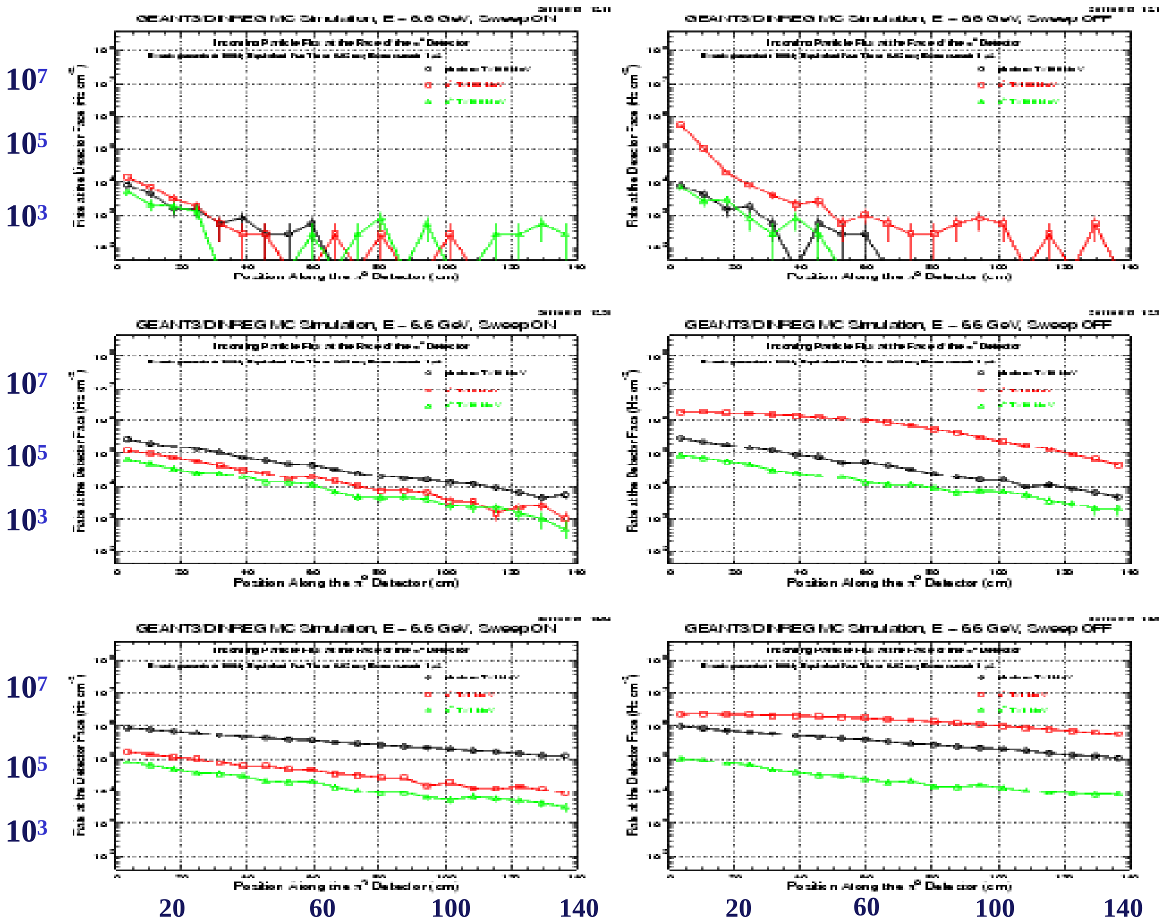
Transmission of the same PbF_2 samples after a 10 minute exposure to 365 nm UV light .

(Adopted from D. F. Anderson and E. J. Ramberg, FERMILAB-Conf-90/46)

- ➔Modest damage for $PbWO_4$ and PbF_2 crystals occurs at ~30-50 krad. The damage can be easily removed by UV optical bleaching.
- ➔$PbWO_4$ degradates by 2-3% for dose rates 15-20 krad/hr and below 10 krad integrated doses. (L. Nagornaya et al., IEEE Trans. On Nucl. Science, 44, 866, 1997).
- ➔For integrated doses of 1-2 Mrad the radiation damage is ~5% at dose rate 100 krad/hr and is ~10-25% at dose rates of ~500 krad/hr. (R. Y. Zhu et al., IEEE Trans. On Nucl. Science 45, 686, 1998).

Background conditions (expected rates)

The major sources contributing to the dose in π^0 experiment are the target-induced rates and beam-line components.

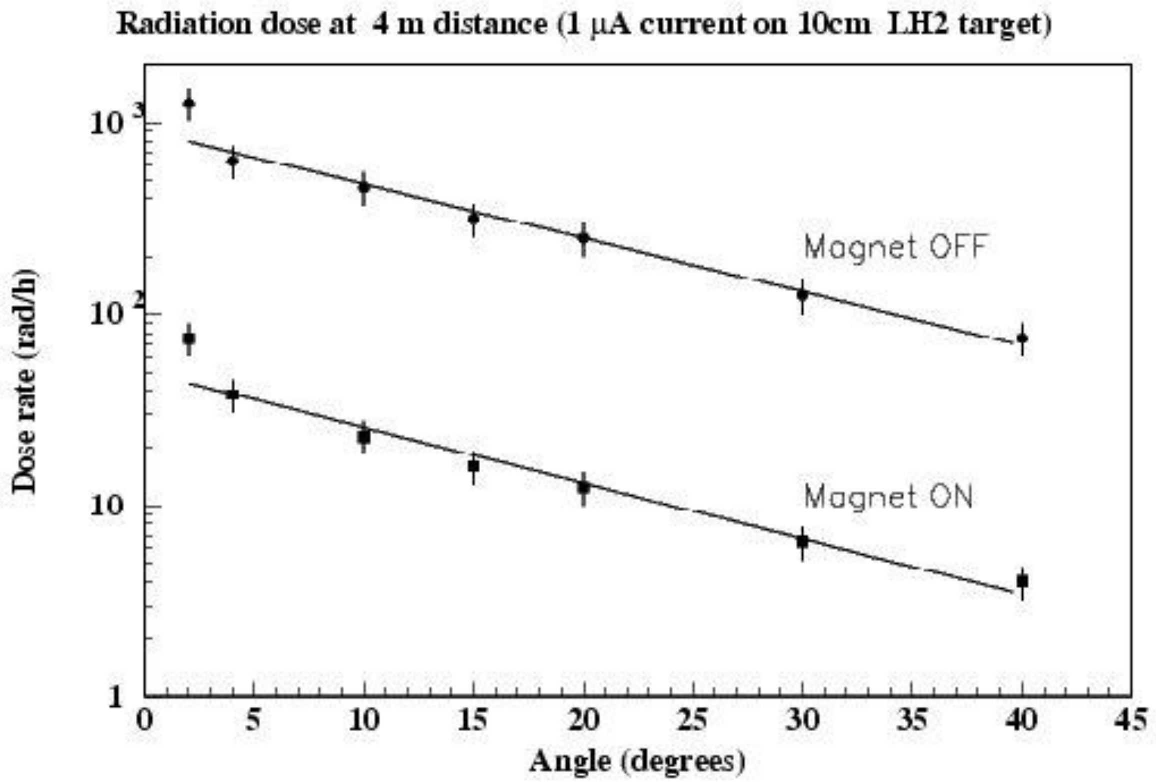


Beam energy: 6.6 GeV
Beam current: 1 μA
Target: 10 cm LH2
Solid angle: 10 msr

Background conditions for the other experiments would be similar if the measurements were taken under same conditions .

The flux of the γ, e^- and e^+ (in Hz/cm^2) at the face of the π^0 detector as a function of the position (in cm) at three energy thresholds (from top to bottom 100, 10 and 1 MeV). Left: sweeping magnet is ON; Right: sweeping magnet is OFF. (From Pavel Degtiarenko)

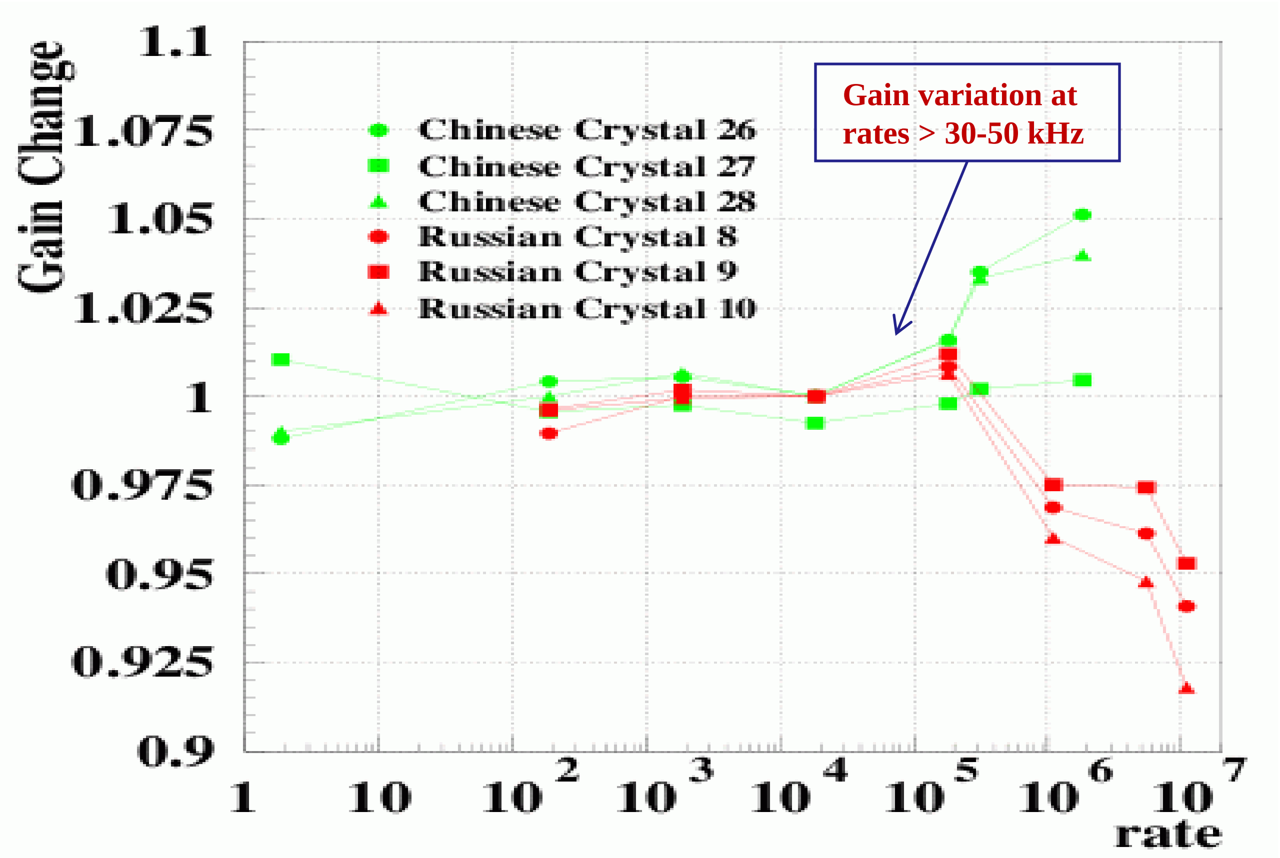
Background conditions (dose rates)



- The damage is worst at the front of the crystals (first 2-4 cm), since most of the background are low energy photons.
- The flux of photons drops by factor of ~100 for energy range from 0.5 MeV to 20 MeV
- At the smallest angle 5.5 degrees the dose rate is ~400-500 rad/hr for the sweeping magnet field OFF and ~40-50 rad/hr for the field ON configuration
- UV curing from the face of the calorimeter can reverse Transmission of the crystals

The PMT gain variation with rate

Hamamatsu PMTs R4125 used in HYCAL.

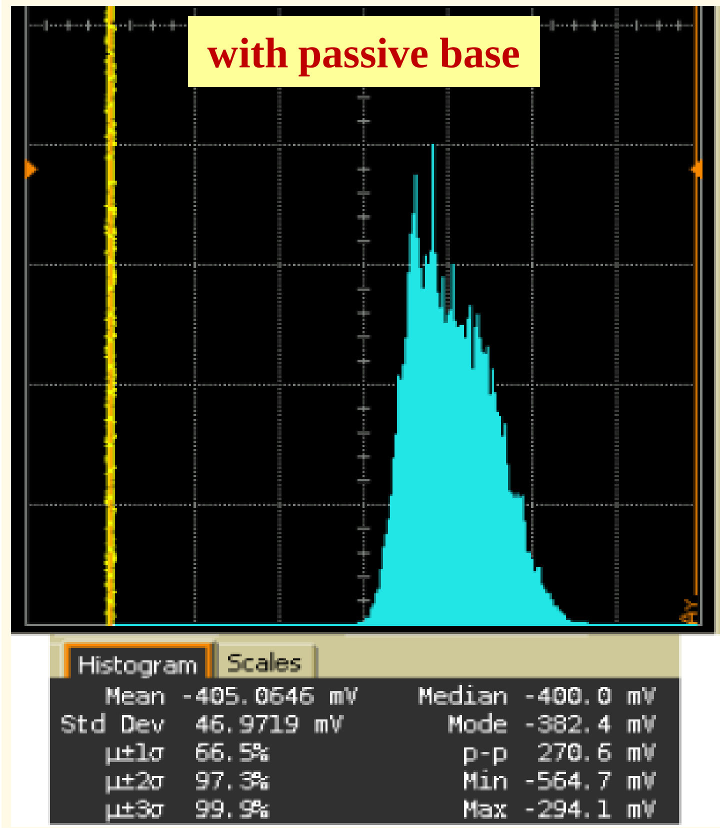


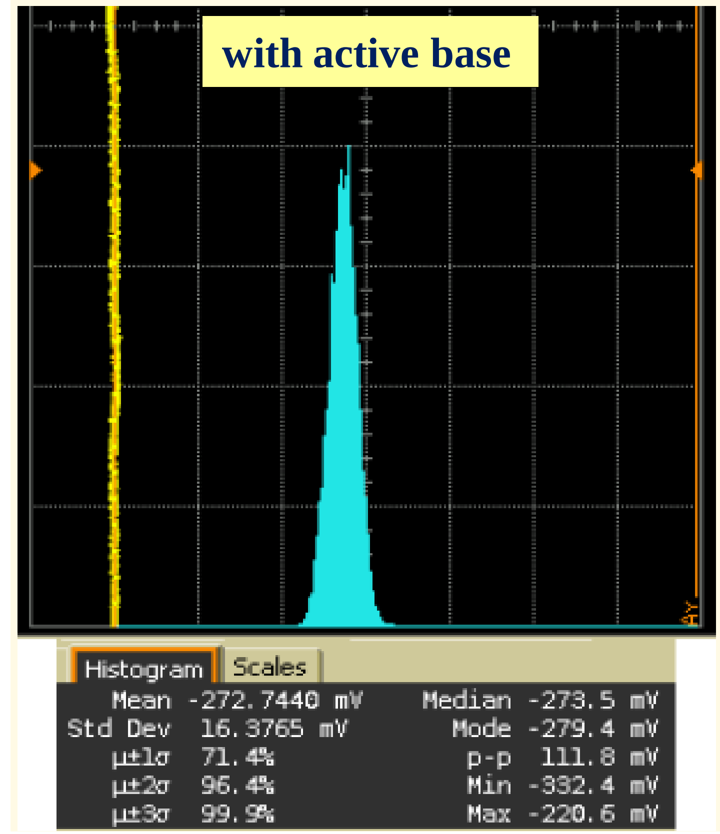
Variation of the PMT gain of $PbWO_4$ crystals as tested for the PRIMEX apparatus, as a function of the rate induced in electron beam test. (Adopted from PRIMEX).

Active base with amplifier powered from current flowing through high voltage divider was developed and tested by Vladimir Popov.

Active HV base tests

Active HV base has been tested by Vladimir Popov:





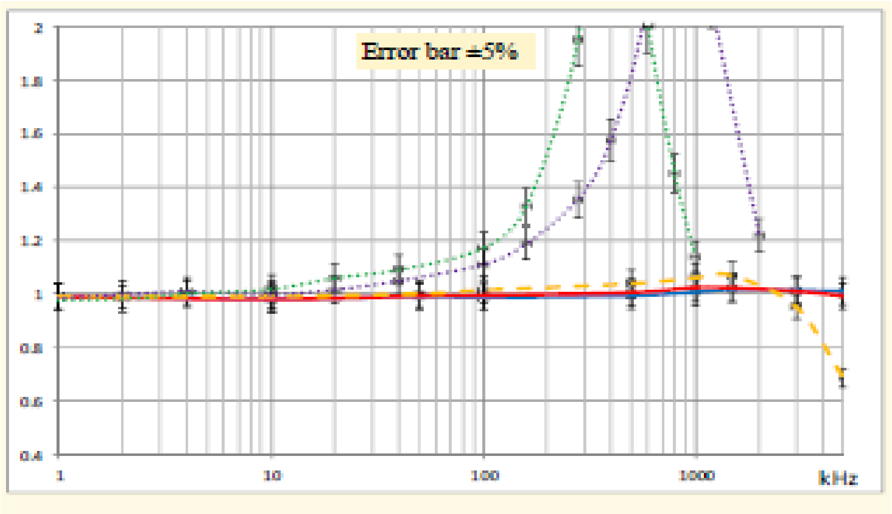
The PMT amplitude distribution with passive base with light pulse frequency varying within 1–100 kHz range with period of 100 ns.

The PMT amplitude distribution with active base with light pulse frequency varying within 0.1–1.5 MHz range with period of 100 ns.

(Adopted from V. Popov)

Active HV base tests

Active HV base test with LED light source similar to $PbWO_4$ scintillator (by Vladimir Popov)



Normalized gain as a function of pulse repetition rate:

Active base initial amplitude:
---- 300 mV; --- 600 mV; - - - 1000 mV

Passive base initial amplitude:
….. 300 mV; ….. 600 mV

(Adopted from V. Popov)

Comparison of the original PrimEx base with modified active base design.

Parameter	PrimEx HV base	Active HV base
Maximum anode current	~6 µA, gain variation ±5%	~16 µA, gain variation ±1%
Maximum output pulse	unknown	-4 V, (-80 mA/50 Ohm)
Divider current	170 µA at 1.5 kV	450 µA at 1.1 kV
Maximum linear count rate	30 kHz ±5%	1.2 MHz ±1%

Background test results

Radiation hardness of designed circuit was tested during Qweak experiment.
After receiving a > 150 krad dose no changes were observed.

Geometric efficiencies for $PbWO_4$ & PbF_2

Simulation performed by Vardan Tadevosyan. The size for the calorimeters are taken:
$PbWO_4$ -- from π^0-proposal (size 58×70 cm^2, or 29×35 matrix of 2.0×2.0 cm^2 crystals)
PbF_2 – from E07-007 proposal (size 39×48 cm^2, or 13×16 matrix of 3.0×3.0 cm^2 crystals).
The low threshold on the energy deposition is taken 100 MeV, detectors at 6.54 degrees.

υ (MeV)	z	Pπ (MeV/c)	PbWO4@4m Eff ± err (%)	PbWO4@3m Eff ± err (%)	PbF2@3m Eff ± err (%)
5330.0	0.40	2132.0	9.31±0.02	23.23±0.04	5.35±0.02
5330.0	0.50	2665.0	19.98±0.04	35.15±0.05	14.83±0.04
5330.0	0.60	3198.0	29.52±0.05	45.22±0.05	24.07±0.04
5330.0	0.70	3731.0	37.86±0.05	53.75±0.05	32.23±0.05
5330.0	0.80	4264.0	45.30±0.05	60.89±0.05	39.54±0.05
5330.0	0.90	4797.0	51.74±0.05	67.18±0.05	46.03±0.05
5330.0	1.00	5330.0	57.50±0.05	72.48±0.04	51.80±0.05

The geometric efficiency of the π^0 detector was estimated by means of MC. Direction of π^0 was sampled within the geometric acceptance of the detector with subsequent $\pi^0 \to 2\gamma$ decay. The fraction of events where both γ's were detected was used to calculate the geometric acceptance.

Note, the results for PbWO4@4m are slightly different than in Table I in PAC39 proposal.
The main reason can be related to the target length (point-like in proposal, while here is 10 cm).

π^0 mass reconstruction in $PbWO_4$ & PbF_2

Simulation performed by Vardan Tadevosyan. The size for the calorimeters are taken:
$PbWO_4$ -- from π^0-proposal (size 58×70 cm^2, or 29×35 matrix of 2.0×2.0 cm^2 crystals)
PbF_2 – from E07-007 proposal (size 39×48 cm^2, or 13×16 matrix of 3.0×3.0 cm^2 crystals).
The low threshold on the energy deposition is taken 100 MeV, detectors at 6.54 degrees

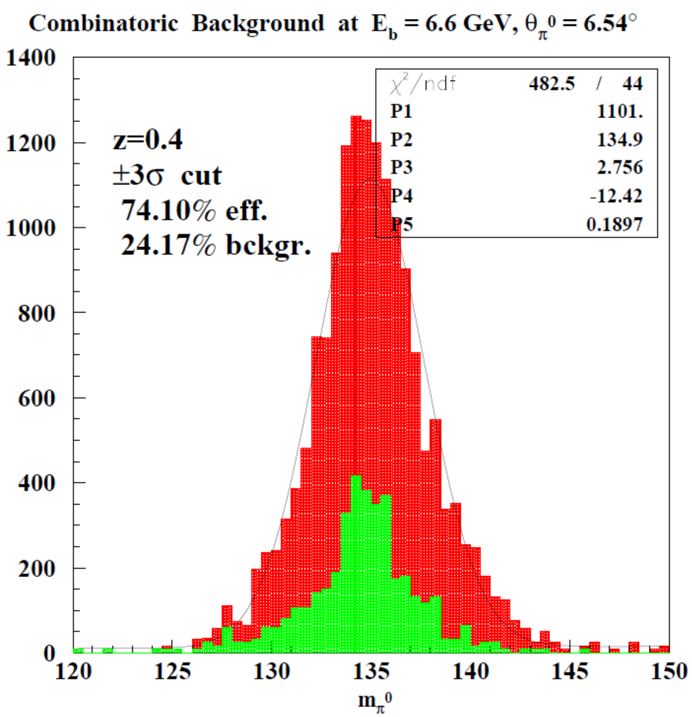
z	PbWO4@3m, 100 ns eff & bkgr (%)		PbWO4@3m, 20 ns eff & bkgr (%)		PbF2@3m, 100ns eff & bkgr (%)		PbF2@3m, 20 ns eff & bkgr (%)	
0.4	74.10	24.17	93.87	5.09	94.17	3.06	98.59	0.31
0.5	72.88	25.21	93.79	5.18	92.33	3.41	98.29	0.60
0.6	78.99	20.00	94.81	4.23	92.82	3.64	98.42	0.55
0.7	82.10	16.22	95.68	3.36	93.68	3.17	98.00	0.45
0.8	85.72	12.72	96.59	2.61	94.84	2.02	98.46	0.24
0.9	88.42	9.64	97.09	2.00	95.55	1.80	98.81	0.25
1.0	91.78	5.69	98.12	1.02	96.59	0.74	98.78	0.14

The quality of reconstruction is noticeably worse for the $PbWO_4$ at 3m. (Due to high background fluxes at small angles seen in the π^0 detector).
The PbF_2 with 100 ns time window is as good as the PbWO4 at 4m.
At 20 ns window both calorimeter comes better.

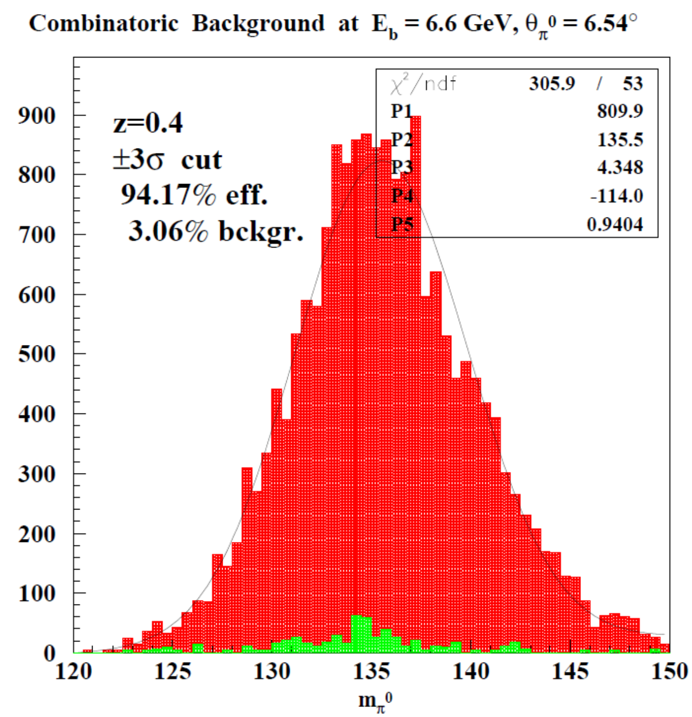
The background here is smaller than in PAC39 proposal due to some differences between the two calculations (in proposal point-like target & detector angle 6.27°).

π^0 mass reconstruction in $PbWO_4$ & PbF_2

Simulation performed by Vardan Tadevosyan. Reconstructed π^0-mass distribution with combinatoric background for $PbWO_4$ (58×70cm^2, 1116 blocks, 2.0×2.0×18cm^3) and PbF_2 (39×48cm^2, 208 blocks, 3.0×3.0×18cm^3), calorimeters at distance of 3 m from the target.



$PbWO_4$



PbF_2

At 6.54° and 3 m distance from the target $PbWO_4$ due to its big size detects all low energy background at ~1°.

At the same distance PbF_2, due to smaller size detects only background at θ_{min} > 2°.

Is any chance to detect η with $PbWO_4$ or PbF_2 ?

Vardan did some estimations to see if any chance to detect η^0

For the $PbWO_4$ calorimeter 64×74 cm^2 (31×36 matrix of 2.05×2.05 cm^2 crystals) at a distance 4m from the target and with threshold energy 100 MeV, the geometrical efficiency for η^0 detection is 0.03% for z = 1, and nearly zero for low z values.

SUMMARY/CONCLUSSION

- Neutral particle detector options based on lead tungstate ($PbWO_4$) and lead fluoride (PbF_2) crystals are considered . These choices are based on the crystal/detector availability at JLab (PrimEx & DVCS.
- The characteristics of the Calorimeters based on these crystals can satisfy most of the requirements variety of planned experiments at 12 GeV energy with detection of photons.
- The basic properties of these crystals (timing, energy & position resolution) are very close, but there are big differences in light emission mechanism, radiation hardness and temperature sensitivity.
- Both crystals, $PbWO_4$ and PbF_2 can handle the high luminosities required by the experiments.
- Fine granularity of the detectors, good energy resolution and high accuracy in the determination of the centre of gravity for the electromagnetic showers, combined with the distance of the detector from the target can provide the necessary angular resolution for the detected photons.
- The use of PMTs for light collection will require special attention at high rates (high anode current). To minimize the PMT gain variation need develop new active HV-bases and gain monitoring systems.
- $PbWO_4$ and PbF_2 are radiation sensitive. To keep high resolution of the detector throughout the experiments requires periodic (after accumulated doses ~30—40 krad) UV curing.
- The light-yield of $PbWO_4$ is temperature-dependent, hence a thermo-stabilizing frame is needed.
- Other options of the calorimeter based on other types of new crystals , and more complicated geometries of the neutral particle detector are not considered here. The options presented are likely the most suitable for the planned experiments both economically and practically.

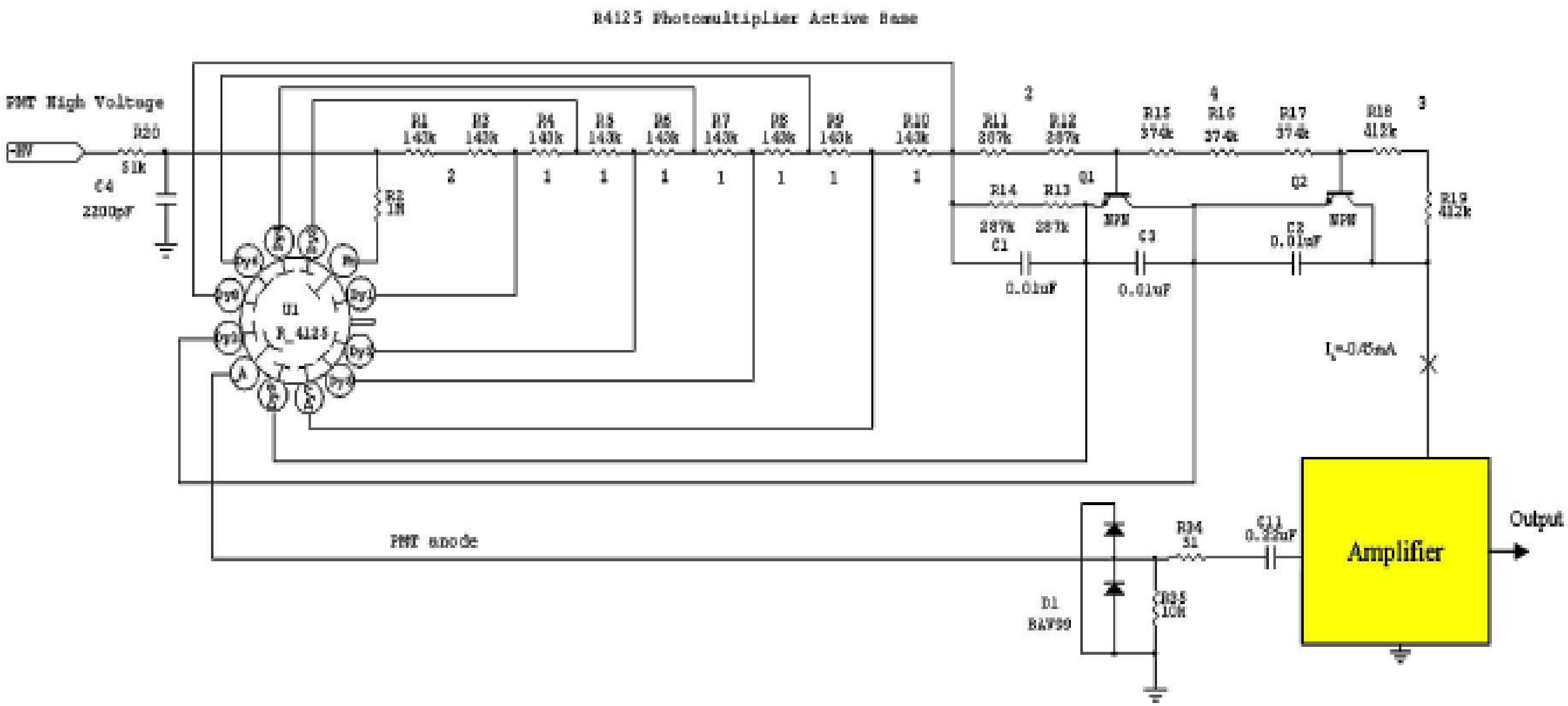
Thanks

Tanja Horn
Rolf Ent
and
Bogdan Wojtsekhowski
for help and many useful comments

Back-up slides

Active HV base for π^0 detector

We are planning to use active HV bases developed by Vladimir Popov



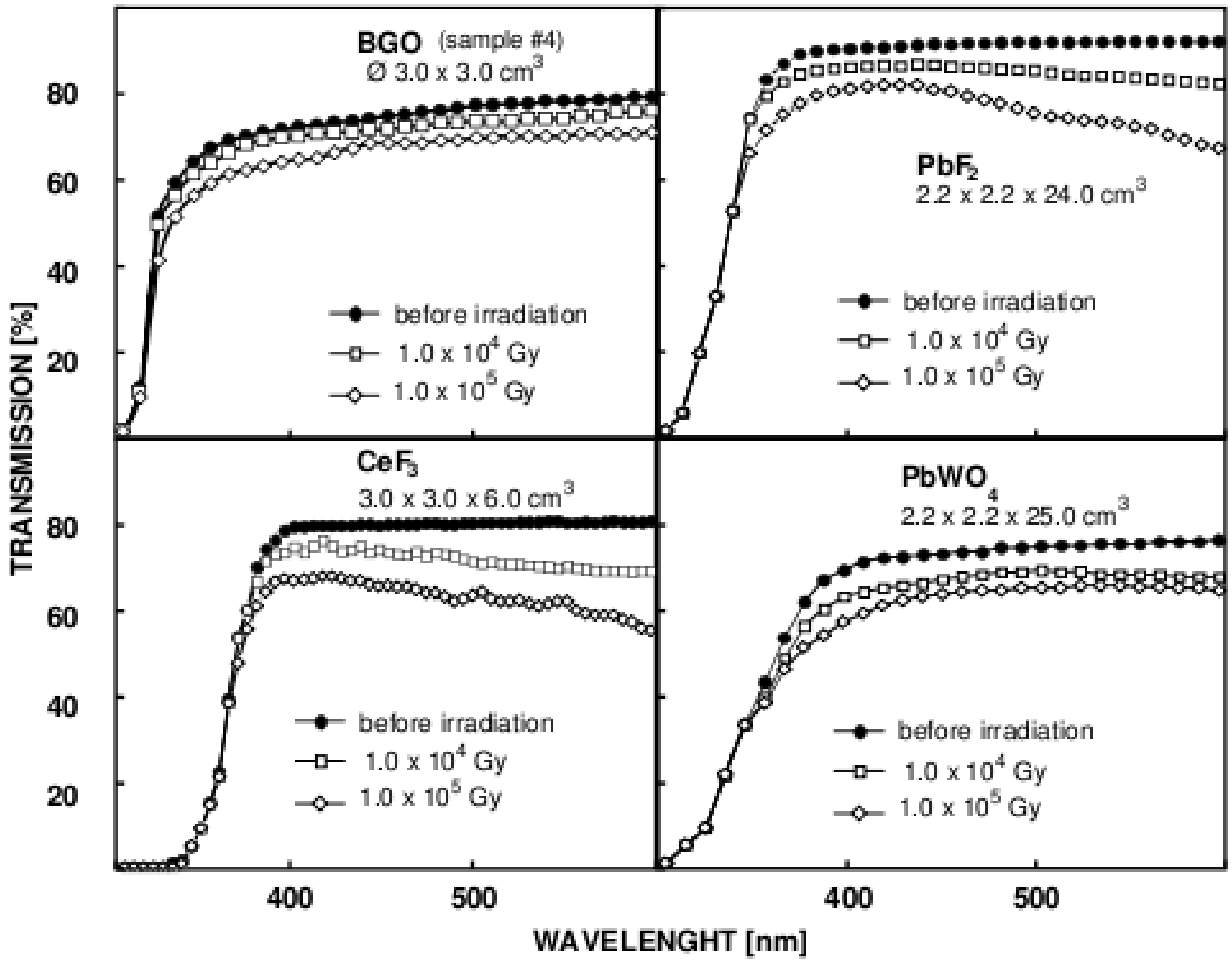
R4125 Photomultiplier tube active base circuit diagram.

Two (Q1, Q2) high voltage transistors are added to the last two dynode power connection nodes. Note, active base circuit does not need additional power.

<u>Note</u>:

Active base with amplifier powered from current flowing through high voltage divider was invented in JLab and successfully used over 10 years as a part of Cherenkov detectors in Halls A & C. (The bases were developed by V. Popov).

Radiation hardness of $PbWO_4$ and PbF_2 crystals



Effect of 1 Mrad accumulated dose on crystal transmission. Recovery of $PbWO_4$ by a few days after the radiation at room temperature. (R. Y. Zhu et al., CMS TN/95-157)

Geometric efficiencies for $PbWO_4$ & PbF_2 calorimeters

(Simulation performed by Vardan Tadevosyan).

For this study the size of the calorimeters are similar:

$PbWO_4$ ➔ size 40×48 cm^2, or 20×24 matrix of 2.0×2.0 cm^2 crystals. Detector at 6.27 degrees.
PbF_2 ➔ size 39×48 cm^2, or 13×16 matrix of 3.0×3.0 cm^2 crystals. Detector at 6.27 degrees.

υ (MeV)	Z	$P\pi^0$ (MeV/c)	PbWO4@3m , 100 ns Efficiency (%)	PbF2@3m, 100 ns Efficiency (%)
5330.0	0.40	2132.0	5.78	5.35
5330.0	0.50	2665.0	15.52	14.83
5330.0	0.60	3198.0	24.82	24.07
5330.0	0.70	3731.0	32.98	32.23
5330.0	0.80	4264.0	40.28	39.54
5330.0	0.90	4797.0	46.74	46.03
5330.0	1.00	5330.0	52.53	51.80

(The low threshold on the energy deposition is taken 100 MeV)

π^0 mass reconstruction in $PbWO_4$ & PbF_2

(Simulation performed by Vardan Tadevosyan).

The size of the calorimeters are
$PbWO_4$ -- size 40×48 cm^2, or 20×24 matrix of 2.0×2.0 cm^2 crystals
PbF_2 – size 39×48 cm^2, or 13×16 matrix of 3.0×3.0 cm^2 crystals.
The low threshold on the energy deposition is taken 100 MeV, detectors at 6.27°.

z	PbWO4@3m , 100 ns Eff. & Bkgr. (%)	PbF2@3m, 100ns Eff. & Bkgr. (%)	PbF2@3m, 20 ns Eff. & Bkgr. (%)
0.4	94.72 3.18	92.73 3.28	98.41 0.56
0.5	94.60 3.52	91.38 4.15	98.32 0.56
0.6	95.36 2.91	93.35 2.79	98.18 0.51
0.7	96.38 2.10	93.50 3.37	97.88 0.54
0.8	95.97 2.11	93.79 2.67	98.40 0.28
0.9	97.17 1.58	95.58 1.80	98.28 0.28
1.0	97.67 0.93	95.96 1.40	98.49 0.09

π^0 mass reconstruction in $PbWO_4$ & PbF_2

(Simulation performed by Vardan Tadevosyan).

For this study the size of the calorimeters are

$PbWO_4$ -- size 40×48 cm^2, or 20×24 matrix of 2.0×2.0 cm^2 crystals

PbF_2 – size 39×48 cm^2, or 13×16 matrix of 3.0×3.0 cm^2 crystals.

The low threshold on the energy deposition is taken 100 MeV, detectors at 6.27°.

Z	PbWO4@3m , 100 ns Eff. & Bkgr. (%)		PbWO4@3m , 20 ns Eff. & Bkgr. (%)		PbF2@3m, 100ns Eff. & Bkgr. (%)		PbF2@3m, 20ns Eff. & Bkgr. (%)	
0.4	94.72	3.18	98.97	0.43	92.73	3.28	98.41	0.56
0.5	94.60	3.52	98.43	0.66	91.38	4.15	98.32	0.56
0.6	95.36	2.91	98.66	0.75	93.35	2.79	98.18	0.51
0.7	96.38	2.10	98.75	0.51	93.50	3.37	97.88	0.54
0.8	95.97	2.11	99.14	0.40	93.79	2.67	98.84	0.28
0.9	97.17	1.58	99.32	0.26	95.58	1.80	98.28	0.28
1.0	97.67	0.93	99.28	0.12	95.96	1.40	98.49	0.09

π^0 mass reconstruction in $PbWO_4$ & PbF_2

Simulation performed by Vardan Tadevosyan. The size for the calorimeters are taken:
$PbWO_4$ -- from π^0-proposal (size 58×70 cm^2, or 29×35 matrix of 2.0×2.0 cm^2 crystals)
PbF_2 – from E07-007 proposal (size 39×48 cm^2, or 13×16 matrix of 3.0×3.0 cm^2 crystals).
The low threshold on the energy deposition is taken 100 MeV, detectors at 6.54 degrees

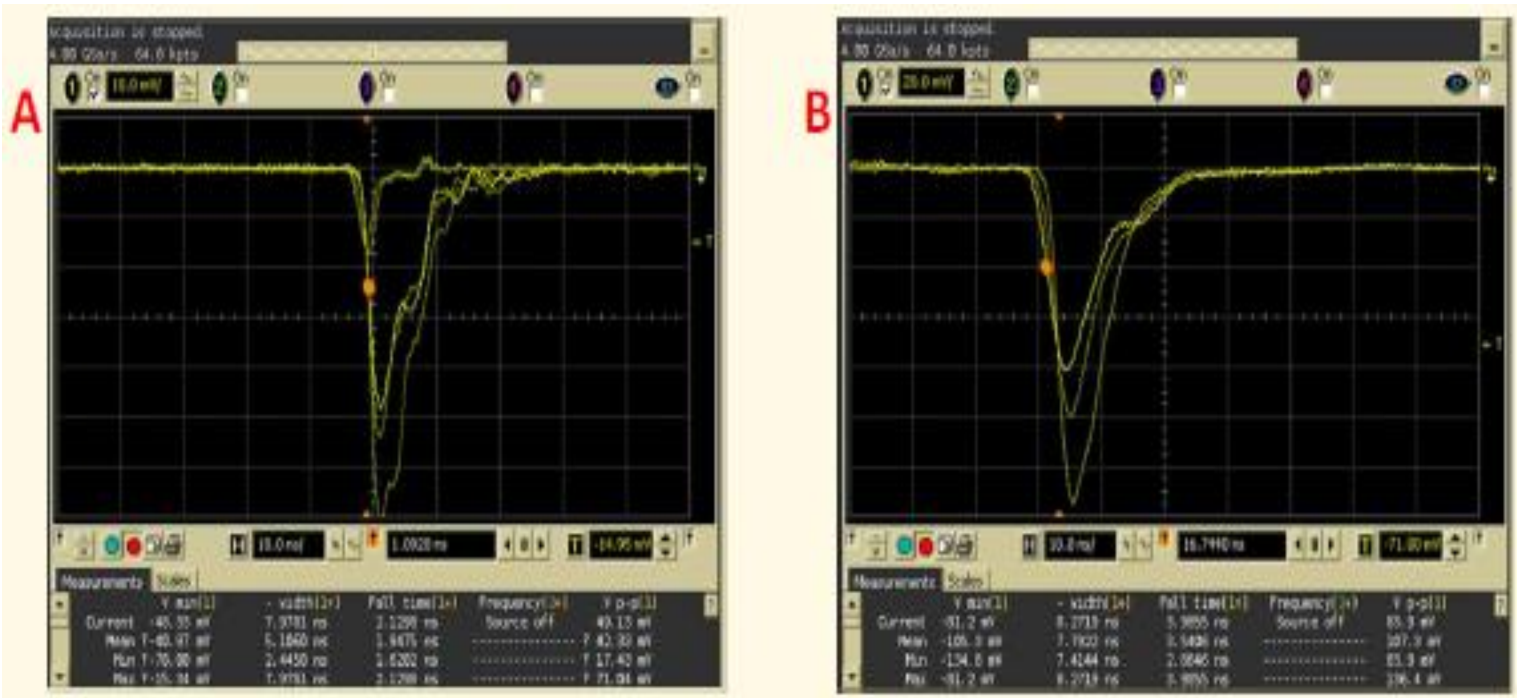
z	PbWO4@4m, 100 ns eff & bkgr (%)	PbWO4@3m , 100 ns eff & bkgr (%)	PbF2@3m, 100ns eff & bkgr (%)	PbF2@3m, 20 ns eff & bkgr (%)
0.4	95.03 3.70	74.10 24.17	94.17 3.06	98.59 0.31
0.5	94.88 3.68	72.88 25.21	92.33 3.41	98.29 0.60
0.6	95.37 3.36	78.99 20.00	92.82 3.64	98.42 0.55
0.7	96.44 2.52	82.10 16.22	93.68 3.17	98.00 0.45
0.8	96.45 2.30	85.72 12.72	94.84 2.02	98.46 0.24
0.9	97.46 1.58	88.42 9.64	95.55 1.80	98.81 0.25
1.0	98.12 0.92	91.78 5.69	96.59 0.74	98.78 0.14

The quality of reconstruction is noticeably worse for the $PbWO_4$ at 3m. (Due to high background fluxes at small angles seen in the π^0 detector).
The PbF_2 with 100 ns time window is as good as the $PbWO_4$ at 4m.
At 20 ns window both should get better.

The background here is smaller than in PAC39 proposal due to some differences between the two calculations (in proposal point-like target & detector angle 6.27°).

Active HV base tests

Active HV base have been tested by Vladimir Popov: LED pulse waveforms recorded from the original PrimEx (left) and the redesigned active base (right). The horizontal scale is 20 ns per division, the vertical scale is 100 mV per division, for both images. Both records are acquired at 10 kHz LED pulse frequency.



Output pulse waveform with PMT and PbWO4 scintillator. (A) – with passive base, (B)- with active base. The horizontal scale is 10 ns per division. (Adopted from V. Popov)

$PbWO_4$ & PbF_2 crystals

- **To improve the radiation resistance of the crystals usually they are doped with a small amount (40—100 ppm) of Nb**
- **Measurements indicate that $PbWO_4$ crystals produced by different manufactures have different spectra, and some crystals may have significant slow components, depending on impurity (concentration and type of doped material). (M. Kobayashi et al., Proc. Int. Conf. On Inorg. Scint. And they Applic., Delft, Aug., 1995).**
- **The major sources contributing to the dose in π^0 experiment are the target-induced rates and beam-line components (beam pipe, vacuum flanges, …).**
- **Light monitoring system to provide monitoring, stability and quality control of the crystals and PMTs are needed !**
- **Temperature stabilization system for $PbWO_4$ are needed**
- **The UV optical bleaching needed to remove radiation damage.**

Geometric efficiencies: $PbWO_4$ & Shashlik calorimeters

(Simulation performed by Vardan Tadevosyan).

$PbWO_4$ -- 2.0×2.0 cm^2 crystals, 40×48 cm^2 (20×24 matrix) at 3m, 58×70 cm^2 (29×35 matrix) at 4m. Shashlik type calorimeter – 5×5 cm^2 modules, 45×55 cm^2 (9×11 matrix) at 3m, 60×70 cm^2 (12×14 matrix) at 4m. Energy and position resolutions: $\sigma/E = 2.1\%+6.2\%/\sqrt{E}$, $\sigma x = 1.4mm+5.9mm/\sqrt{E}$ (from PHENIX). The low threshold on the energy is 100 MeV. (PbWO4 at 6.27^o & 6.54^o, Shashlik calorimeter at 6.27^o).

υ (MeV)	Z	$P\pi^0$ (MeV/c)	PbWO4 Efficiency (%)		Shashlik calorimeter Efficiency (%)	
			3m	4m	3m	4m
5330.0	0.40	2132.0	5.78	9.31	10.96	10.04
5330.0	0.50	2665.0	15.52	19.98	21.92	20.85
5330.0	0.60	3198.0	24.82	29.52	31.43	30.52
5330.0	0.70	3731.0	32.98	37.86	39.94	38.95
5330.0	0.80	4264.0	40.28	45.30	47.23	46.32
5330.0	0.90	4797.0	46.74	51.50	53.80	52.79
5330.0	1.00	5330.0	52.53	57.50	59.59	58.60

The geometric efficiencies for "Shashlik" type calorimeter and $PbWO_4$ are close. The efficiency is governed primarily by solid angle of detector, which is kept ~constant.

π^0 mass reconstruction: $PbWO_4$ & Shashlik

(Simulation performed by Vardan Tadevosyan).

$PbWO_4$ -- 2.0×2.0 cm^2 crystals, 40×48 cm^2 (20×24 matrix) at 3m, 58×70 cm^2 (29×35 matrix) at 4m. Shashlik type calorimeter – 5×5 cm^2 modules, 45×55 cm^2 (9×11 matrix) at 3m, 60×70 cm^2 (12×14 matrix) at 4m. Energy and position resolutions: $\sigma/E = 2.1\%+6.2\%/\sqrt{E}$, $\sigma x = 1.4mm+5.9mm/\sqrt{E}$ (from PHENIX). The low threshold on the energy is 100 MeV. (PbWO4 at 6.27^o & 6.54^o, Shashlik calorimeter at 6.27^o).

z	PbWO4@3m eff & bkgr (%)		PbWO4@4m eff & bkgr (%)		Shashlik@3m eff & bkgr (%)		Shashlik@4m eff & bkgr (%)	
0.4	94.72	3.18	95.03	3.70	76.51	18.76	84.35	13.00
0.5	94.60	3.52	94.88	3.68	76.33	18.99	83.63	13.49
0.6	95.36	2.91	95.37	3.36	78.49	17.12	84.26	12.96
0.7	96.38	2.10	96.44	2.52	81.44	14.59	86.86	10.43
0.8	95.97	2.11	96.45	2.30	84.76	11.55	89.01	8.45
0.9	97.17	1.58	97.46	1.58	82.23	8.20	92.31	5.63
1.0	97.67	0.93	98.12	0.92	91.20	5.43	93.63	4.07

The efficiency of the π^0 mass reconstruction and the associated background for “Shashlik” type calorimeter is noticeably worse than for $PbWO_4$.

Manufactures of $PbWO_4$ & PbF_2 crystals

PbF_2 crystals

- Shanghai Institute of Ceramics and Chinise Academy of Sciences (SICCAS)

Cost ~$500 per crystal PbF_2 with dimensions 3.0cm × 3.0cm ×15cm

$PbWO_4$ crystals

- Bogoroditsk Techno-Chemical Plant, BTCP, (Russia)
- Crytur, (Czech Republic)
- Furukawa, (Japan
- Shanghai Institute of Ceramics, SIC, (China)
- Beijing Glass Research Institute, BGRI, (China)

Estimated price range $2.5-$5.0 per cc.

Main Properties of Heavy Crystals

Param.\crystal	NaI(Tl)	CsI(Tl)	BaF2	**CeF3**	**BGO**	**PbWO4**	**LSO(Ce)**	**PbF2**	**CsI**	**TF-1**
Density (g/cm3)	3.67	4.51	4.89	6.16	7.13	8.3	7.40	7.77	4.53	3.85
Melt. point (C)	651	621	1280	1460	1050	1123	2050	824		
Rad.Length (cm)	2.59	1.86	2.03	1.70	1.12	0.89	1.14	0.93	1.85	2.7
Moliere rad. (cm)	4.13	3.57	3.10	2.41	2.23	2.00	2.07	2.21	3.8	
Inter.length (cm)	42.9	39.3	30,7	23.2	22.7	20.7	20.9	21.0		21.8
Refractive Index	1.85	1.79	1.50	1.62	2.15	2.20	1.82	1.82		1.65
Hydroscopicity	Yes	Slight	No	No	No	No	No	No		No
Emission peak (nm)	410	565	300 220	340 300	480	425 420	420	?	305 480	300- -350
Decay time (ns)	245	1220	650 0.9	30	300	30 10	40	?		
Light Yield (photon/MeV)	4×10^4	5×10^4	?	?	8×10^3	1.5×10^2	?	?	4×10^ 4	?
d(LY)/dT (%/C)	-0.2	0.4	-1.9 0.1	~0	-0.9	-2.5	-0.2	?		
Critical energy										17.5
Rad. hardn. (Gy)	1	10	?	?	1	10^5	?	?	10^3	10^2