Crystals for the Homogeneous Hadron Calorimeter Detector Concept

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Homogeneous Hadron Calorimeter

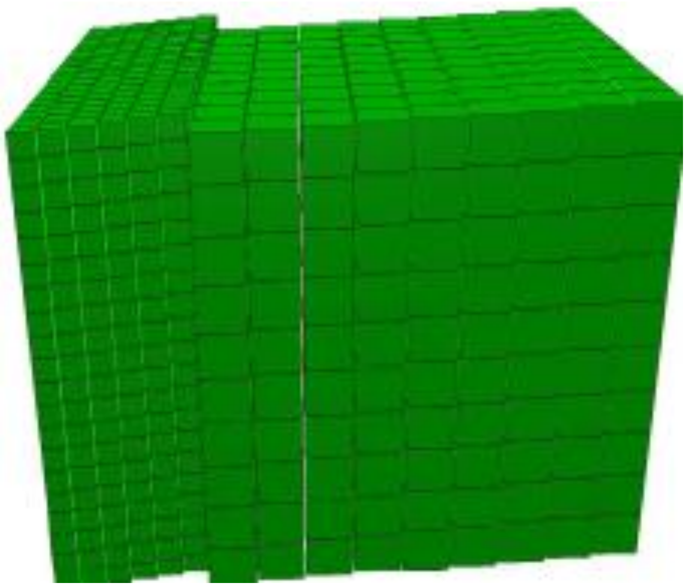
A Fermilab team (A. Para et al.) proposed a total absorption homogeneous HCAL detector concept to achieve good jet mass resolution by measuring both Cherenkov and Scintillation light. It also eliminates the dead materials between classical ECAL and HCAL. This longitudinal segmented crystal HCAL is possible because of the latest development in large area compact readout devices.

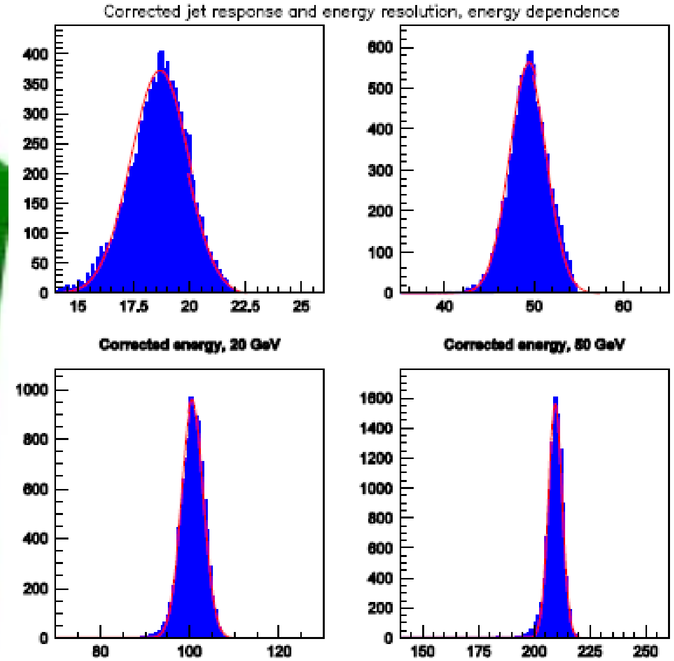
Requirements for the materials to be used for HHCAL:

- Short nuclear interaction length: ~ 20 cm.
- Good UV transmittance: UV cut-off < 350 nm.
- Some scintillation light, not necessary bright and fast.
- Cost-effective material: < \$2/cc for 100 m^3 !
- Radiation hardness is not crucial at the ILC/CLIC.

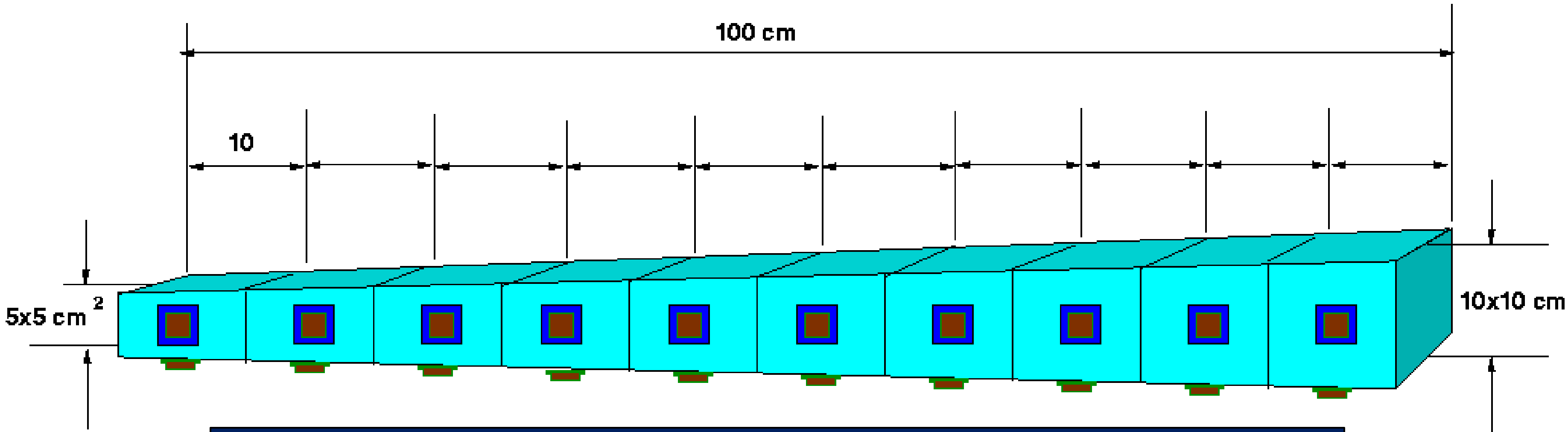
A series of workshops on material development for HHCAL:
1st 2/19/2008 at SIC, Shanghai, 2nd 5/9/2010 at IHEP, Beijing,
3rd 10/30/2010 at Knoxville, will go with SCINT, CALOR & IEEE NSS.

The HHCAL Detector Concept





See A. Para, H. Wenzel, Callor2010: GEANT simulations show a jet energy resolution of better than 20%/√E after corrections.



R.-Y. Zhu, ILCWS-08, Chicago: a HHCAL cell with pointing geometry

Interest of the Community

The 2nd workshops on material development for HHCAL was held on May 9 at Beijing, just one day before Calor2010
BGRI, Caltech, CERN, Fermilab, IHEP, Kharkov, LBL, Ningbo, SIC

Advantages / disadvantages HHCAL concept

R. Wigmans, ***Comments on HHCAL***, *in the 2nd workshop, Beijing*

Advantages:

- *No sampling fluctuations*
- *Some calibration problems characteristic for sampling calorimeters don't play a role*

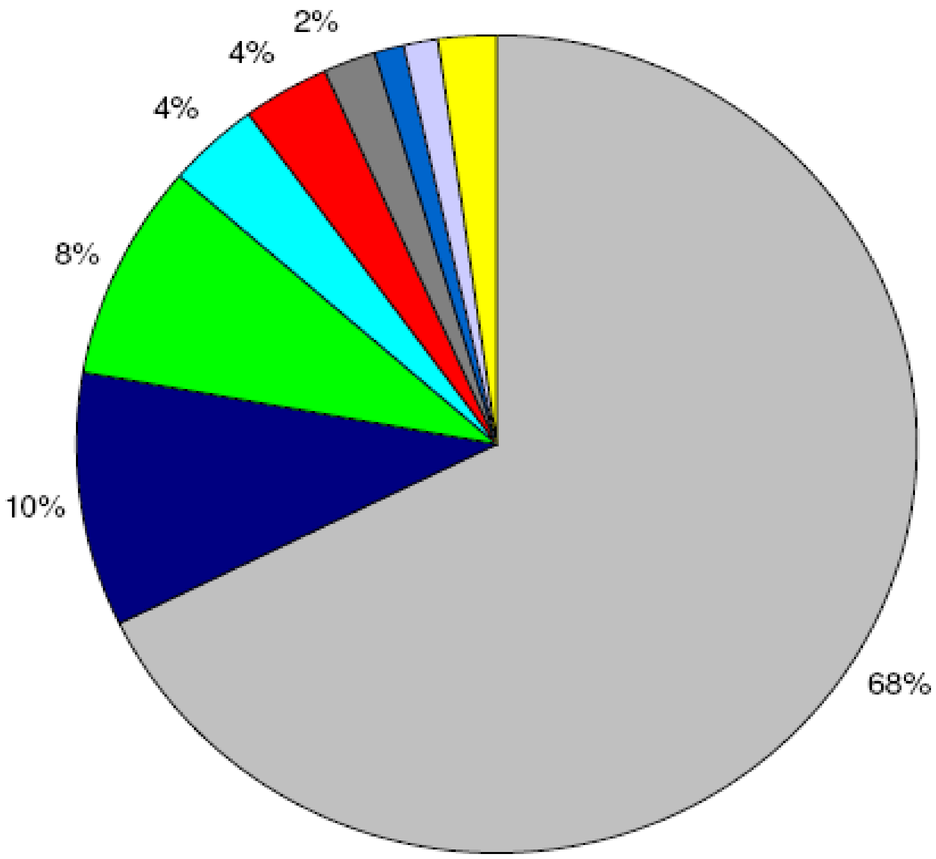
Disadvantages:

The issue of neutrons may be resolved by doping, e.g. Gd, or a long integration time at LC.

- *No sensitivity to neutrons, and thus to invisible energy fluctuations*
- *Light attenuation*
- *Readout*
- *COST*

Cost for Crystal Growth

A. Gektin: for mass produced Si crystals raw materials share 70% of the cost



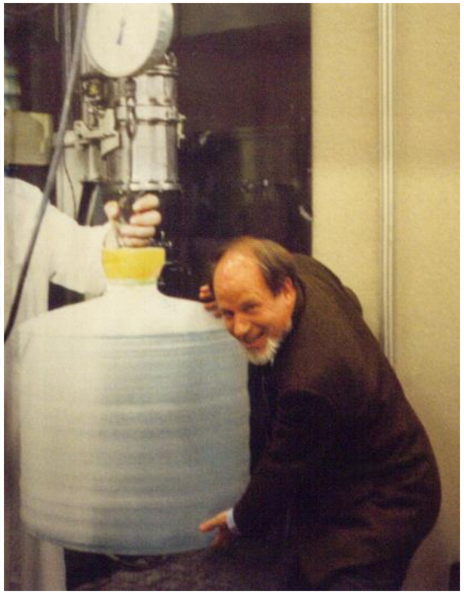
<u>Crystal cost structure (Si)</u>

68% - raw material
10% - crucible
8% - system cost
4% - labor cost
4% - power
6% - other

Single Crystal Si Ingot

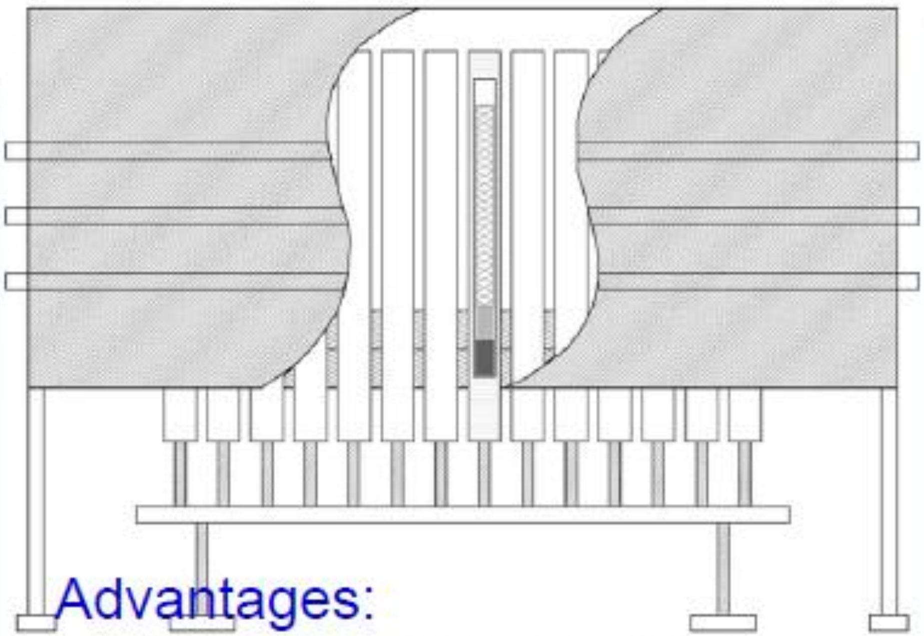
Industrial Halide Growth: Kharkov

A. Gektin: Talk at the 2nd Workshop for HHCAL



Multi-Crucible Bridgman Growth: SICCAS

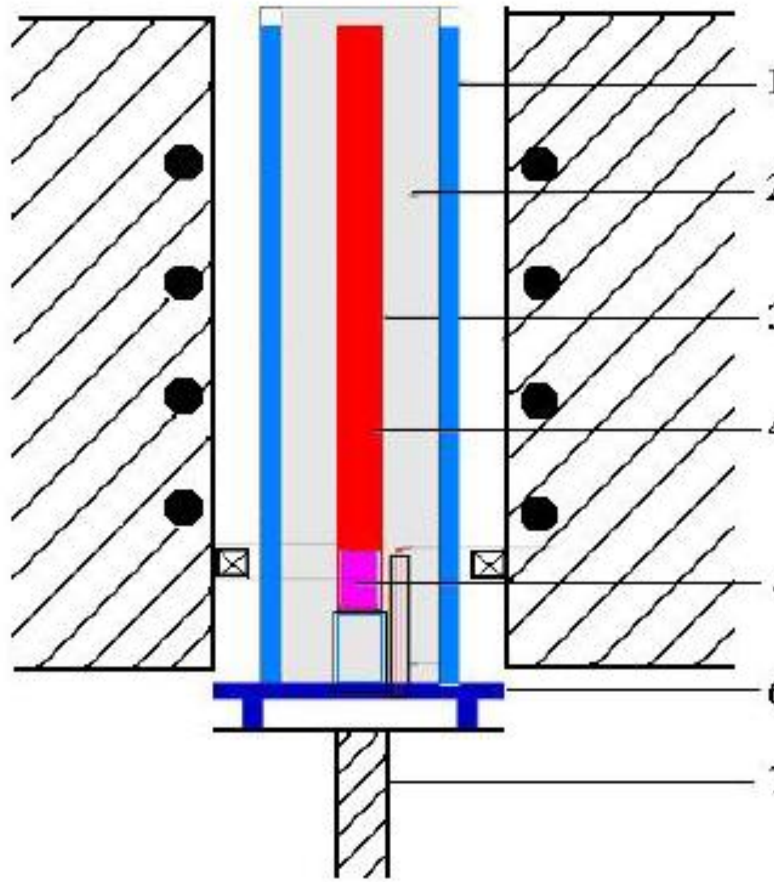
Guohao Ren of SIC: Talk at the 2nd Workshop for HHCAL



Advantages:

Fig. 2. A schematic of a typical Bridgman furnace with 28 crucibles.

1) Low infrastructure investment
2) Simplified the technique
3) Suitable for mass production



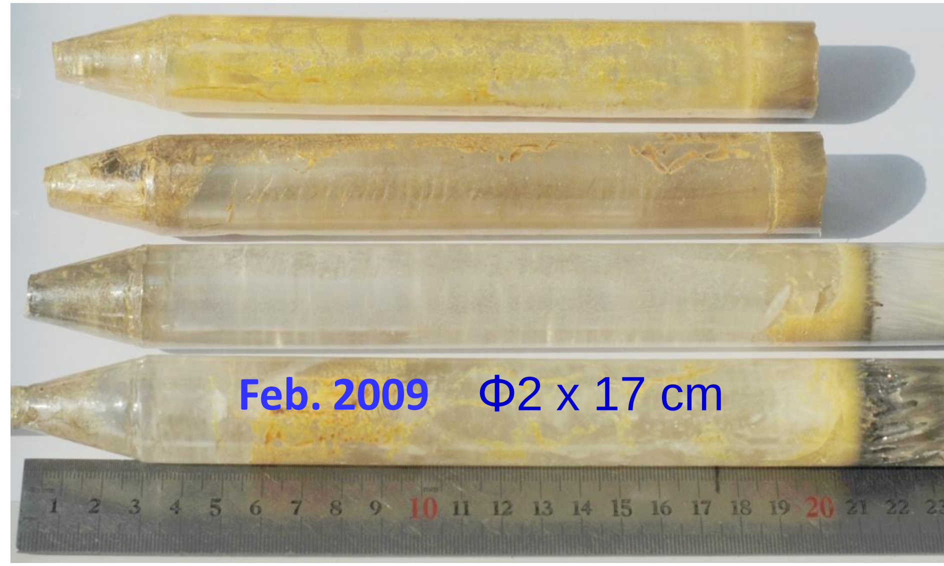
Growth Assembly of Bridgman Method

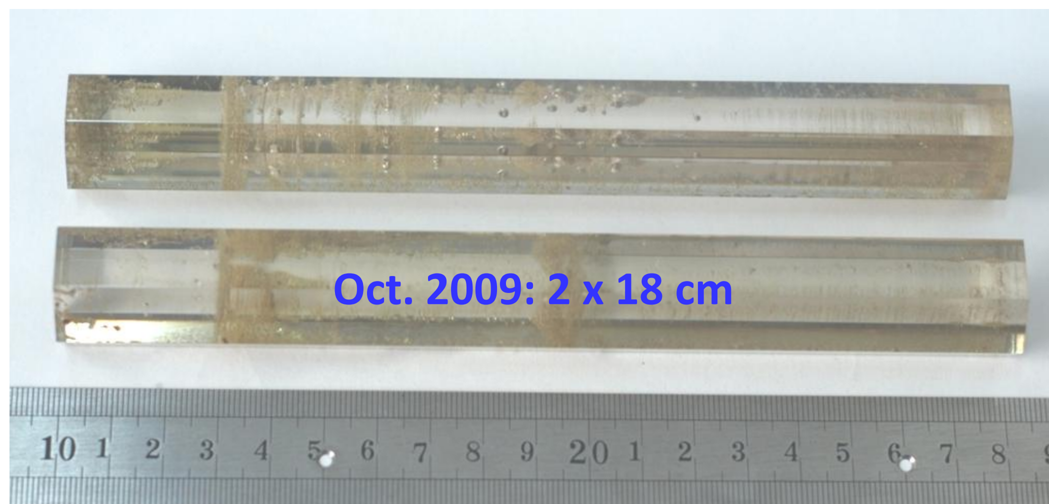
Candidate Crystals for HHCAL

Parameters	$Bi_4Ge_3O_{12}$ (BGO)	$Bi_4Si_3O_{12}$ (BSO)	PbF_2 (PbF)	$PbWO_4$ (PWO)	PbClF
ρ (g/cm^3)	7.13	6.8?	**7.77**	**8.29**	7.11
λ_I (cm)	22.8	23.1	**21.0**	**20.7**	24.3
n @ λ_{max}	2.15	2.06	1.82	2.2	2.15
τ_{decay} (ns)	300	100	**?**	10-30 /10-200	30
λ_{max} (nm)	480	470	**?**	420/512	420
Cut-off λ (nm)	**300**	**295**	**260**	350	**280**
Light Output (%)	100	20	**?**	2	17
Melting point (°C)	**1050**	**1030**	**842**	**1123**	**608**
Raw Material Cost (%)	100	47	**29**	49	**29**

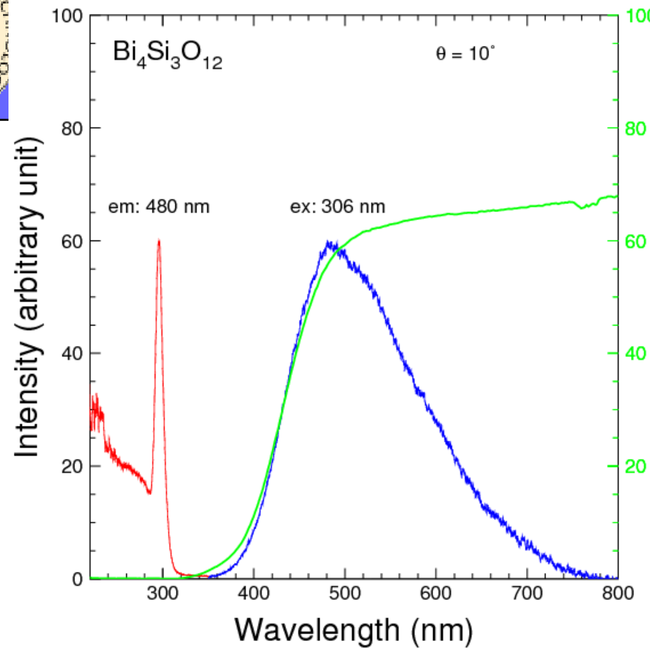
BSO Development at SICCAS

Hu Yuan of SIC: Talk at the 2nd Workshop for HHCAL

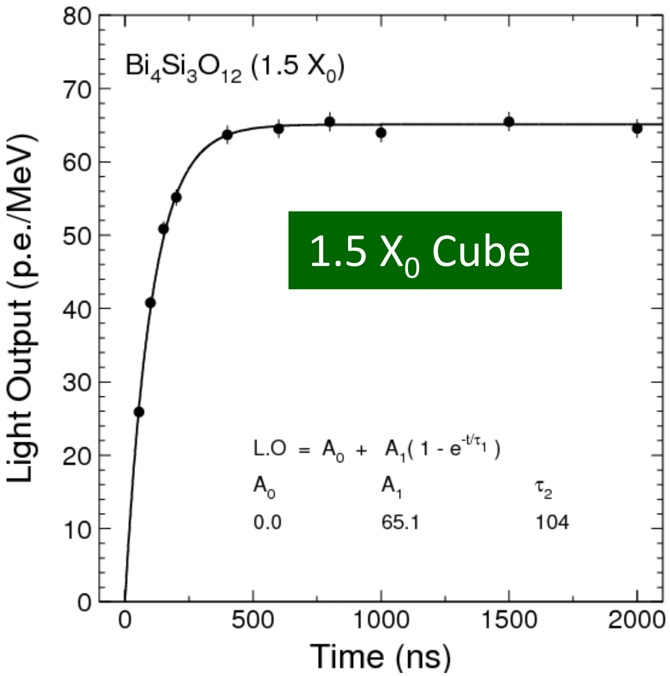




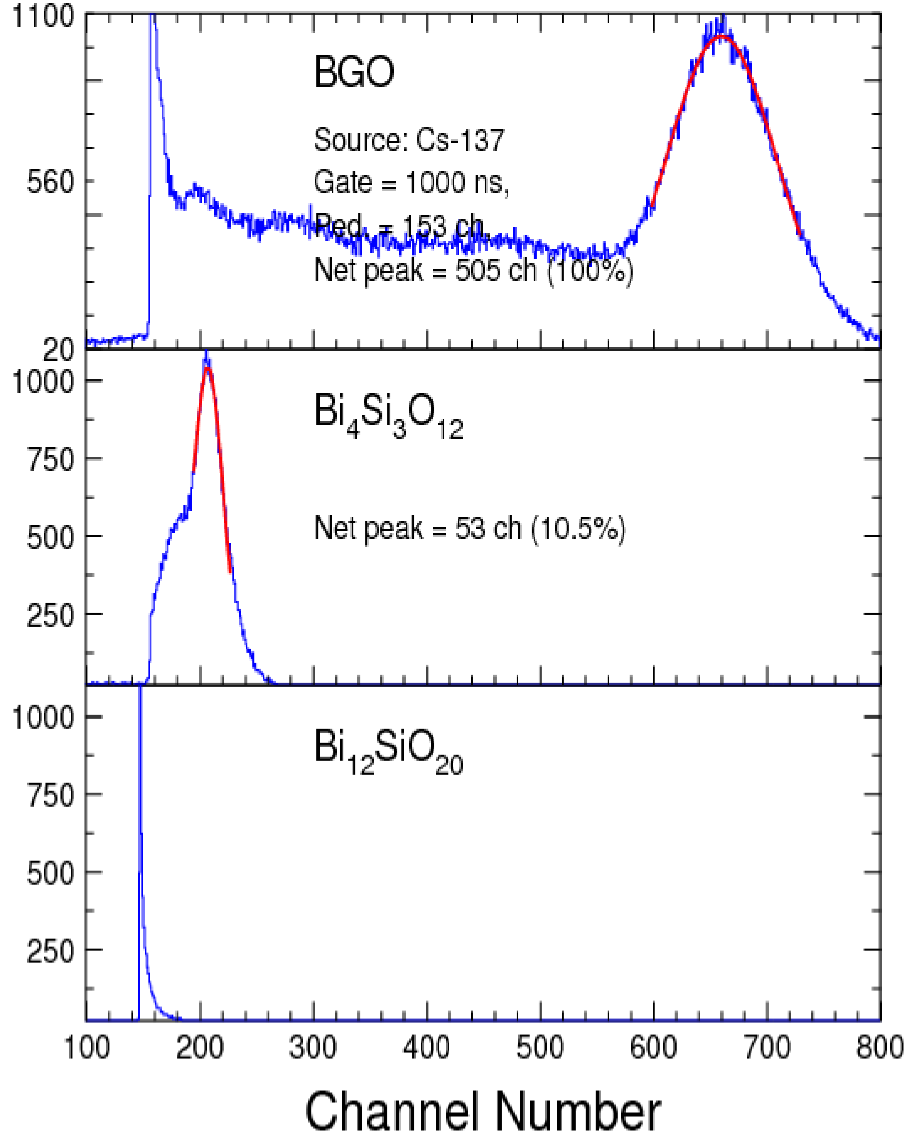
BSO Crystal



$Bi_4Si_3O_{12}$
θ = 10°
em: 480 nm
ex: 306 nm
Intensity (arbitrary unit)
Wavelength (nm)
0
20
40
60
80
100
300
400
500
600
700
800



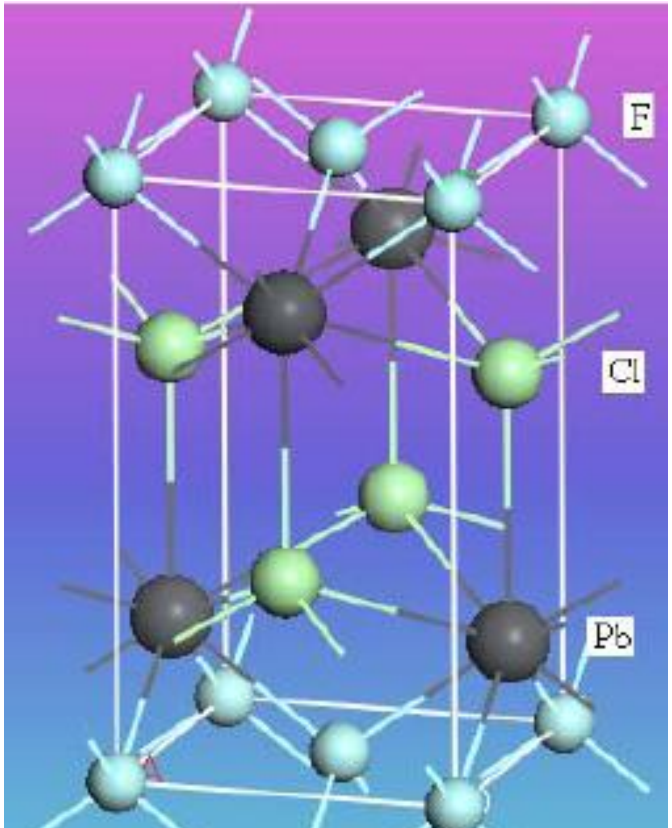
$Bi_4Si_3O_{12}$ (1.5 X_0)
1.5 X_0 Cube
$L.O = A_0 + A_1(1 - e^{-t/\tau_1})$
A_0 A_1 τ_2
0.0 65.1 104
Light Output (p.e./MeV)
Time (ns)
0
10
20
30
40
50
60
70
80
0
500
1000
1500
2000



BGO
Source: Cs-137
Gate = 1000 ns,
Ped. = 153 ch.
Net peak = 505 ch (100%)
$Bi_4Si_3O_{12}$
Net peak = 53 ch (10.5%)
$Bi_{12}SiO_{20}$
Channel Number
20
560
1100
250
500
750
1000
250
500
750
1000
100
200
300
400
500
600
700
800

PbClF Crystal

Guohao Ren of SIC: Talk at the 2nd Workshop for HHCAL



Crystal structure of PbClF

D= 7.11g/cm^3

Melting point =608°C

Space group=P/4nmm

a=4.10Å;c= 7.22Å

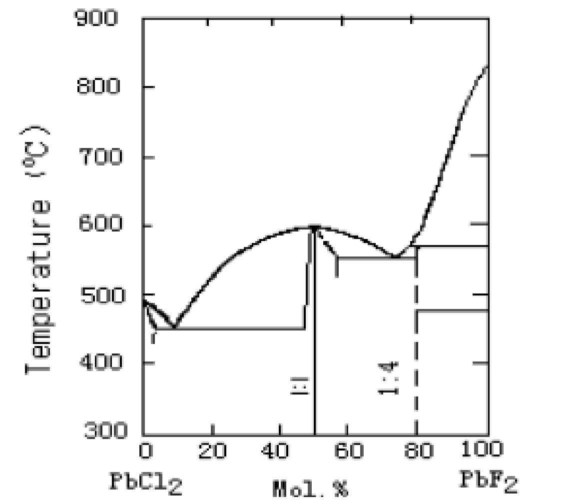
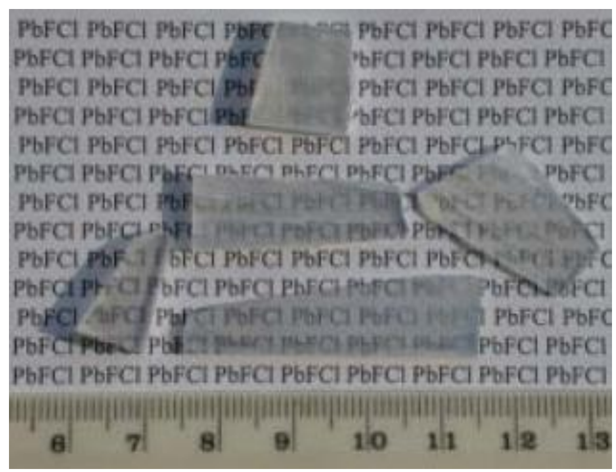


Figure 2.1 Phase relations in $PbCl_2$-PbF_2 system



PbClF Crystal samples grown with Bridgman method

Undoped PbClF Crystal

Guohao Ren of SIC: Talk at the 2nd Workshop for HHCAL

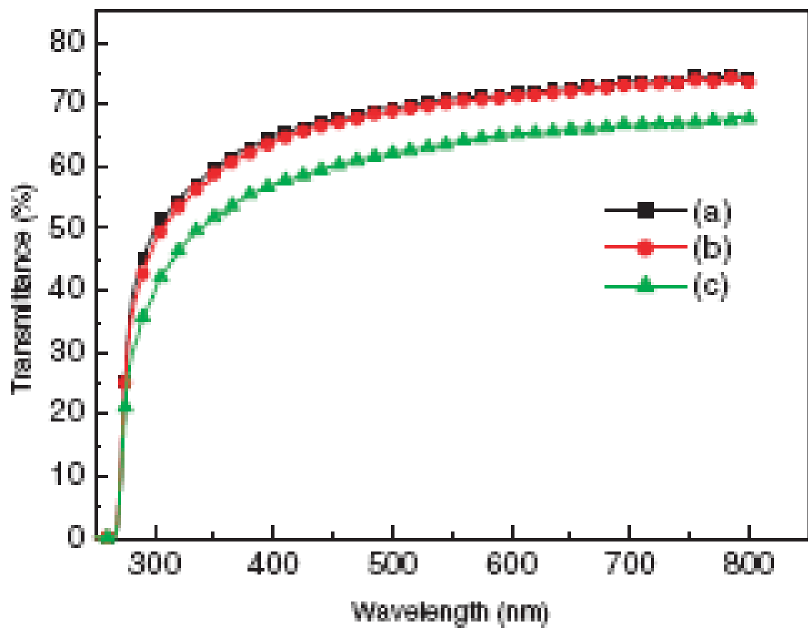


Figure 7. Transmittance curves of PbFCl crystal in 1 mm thick along the [001] direction: (a) before irradiation, (b) after 35 rad h^{-1} × 28 h, (c) after about 500 rad h^{-1} × 48 h.

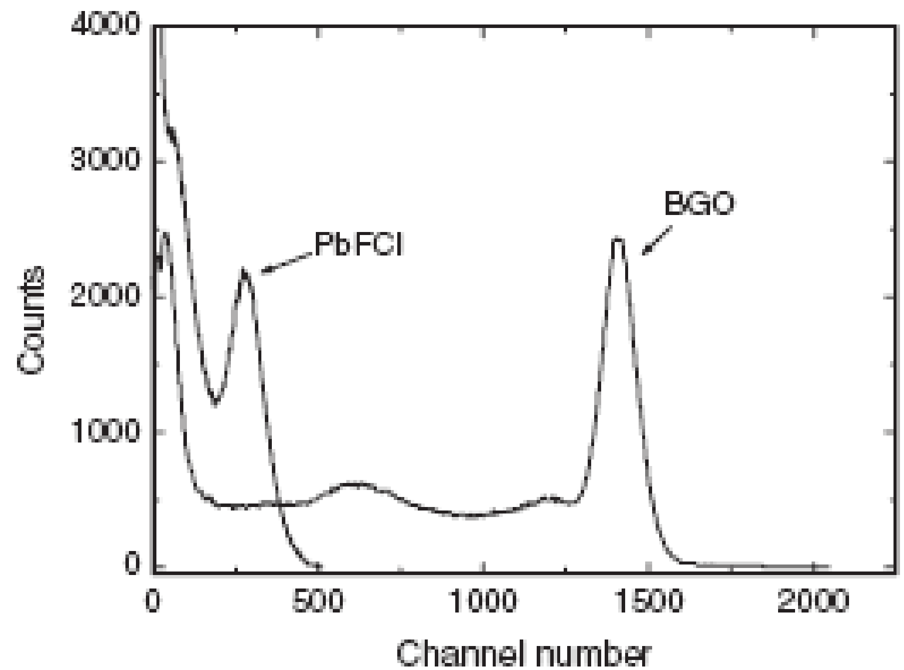
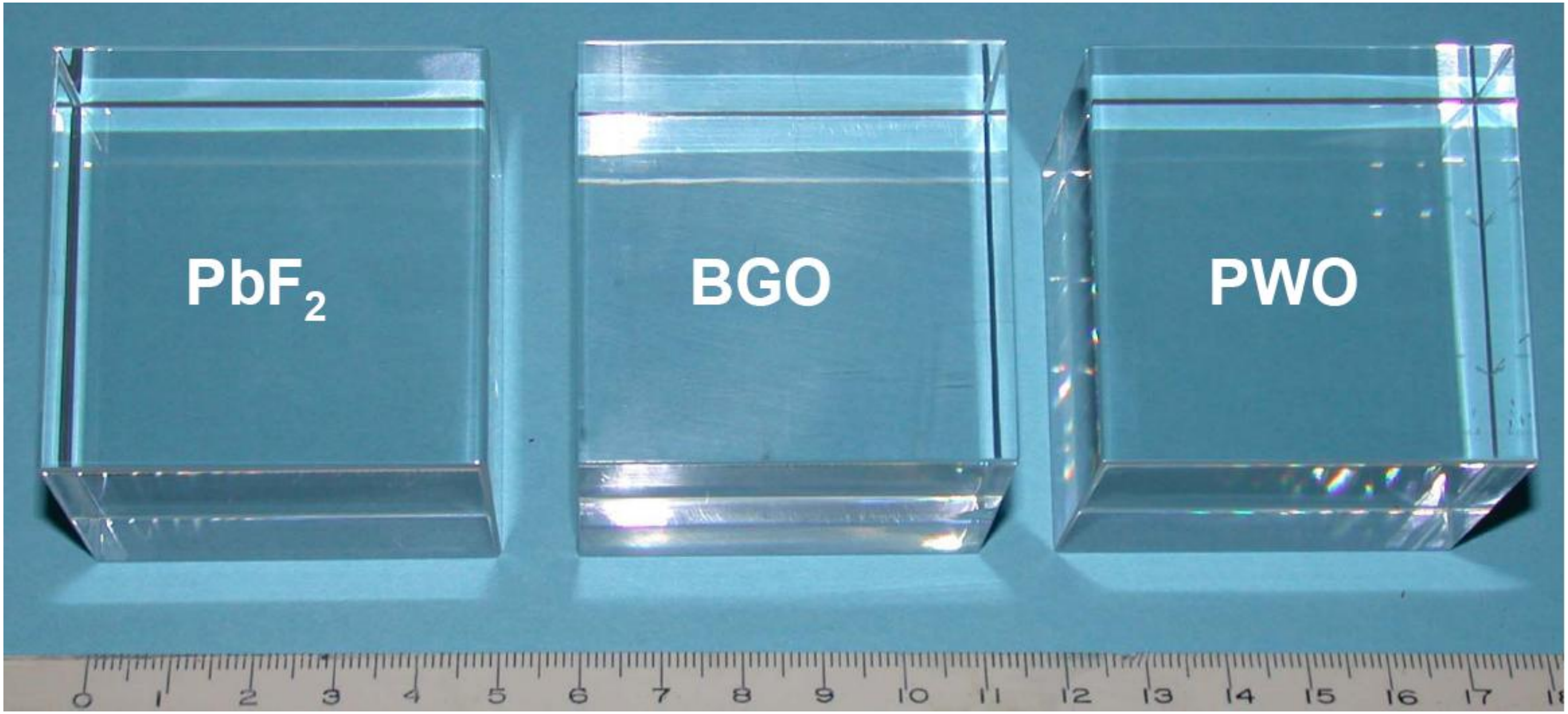


Figure 5. Pulse height spectra of PbFCl and BGO crystals (T = 300 K).

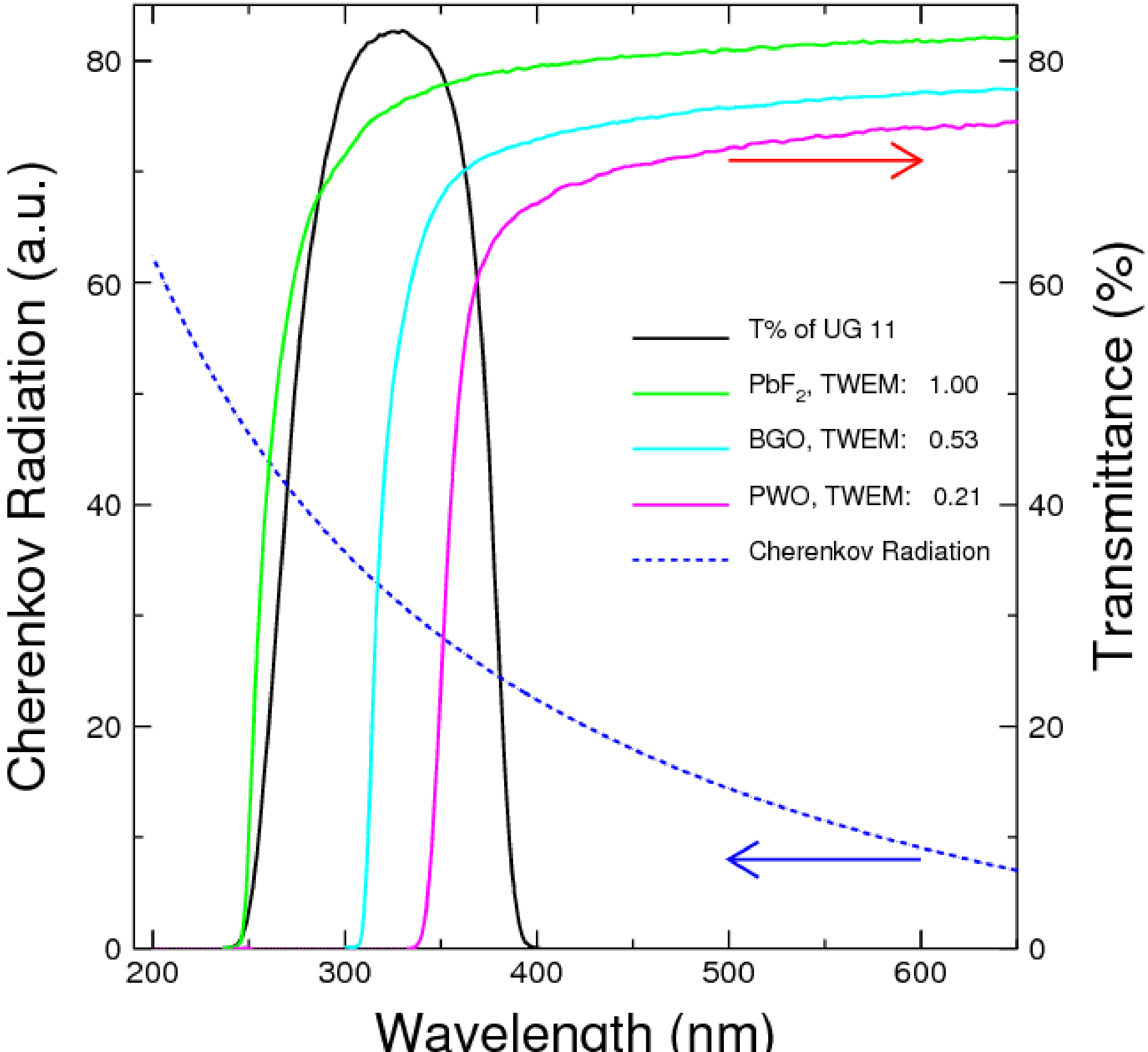
1 mm thick samples

Crystal for Homogeneous HCAL

Crystals of high density, good UV transmittance and some scintillation light, not necessary bright and fast, are required. The volume needed is 70 to 100 m^3: cost-effective material.
Following 2/19/08 workshop at SICCAS, 5 x 5 x 5 cm samples evaluated.



Cherenkov Needs UV Transparency

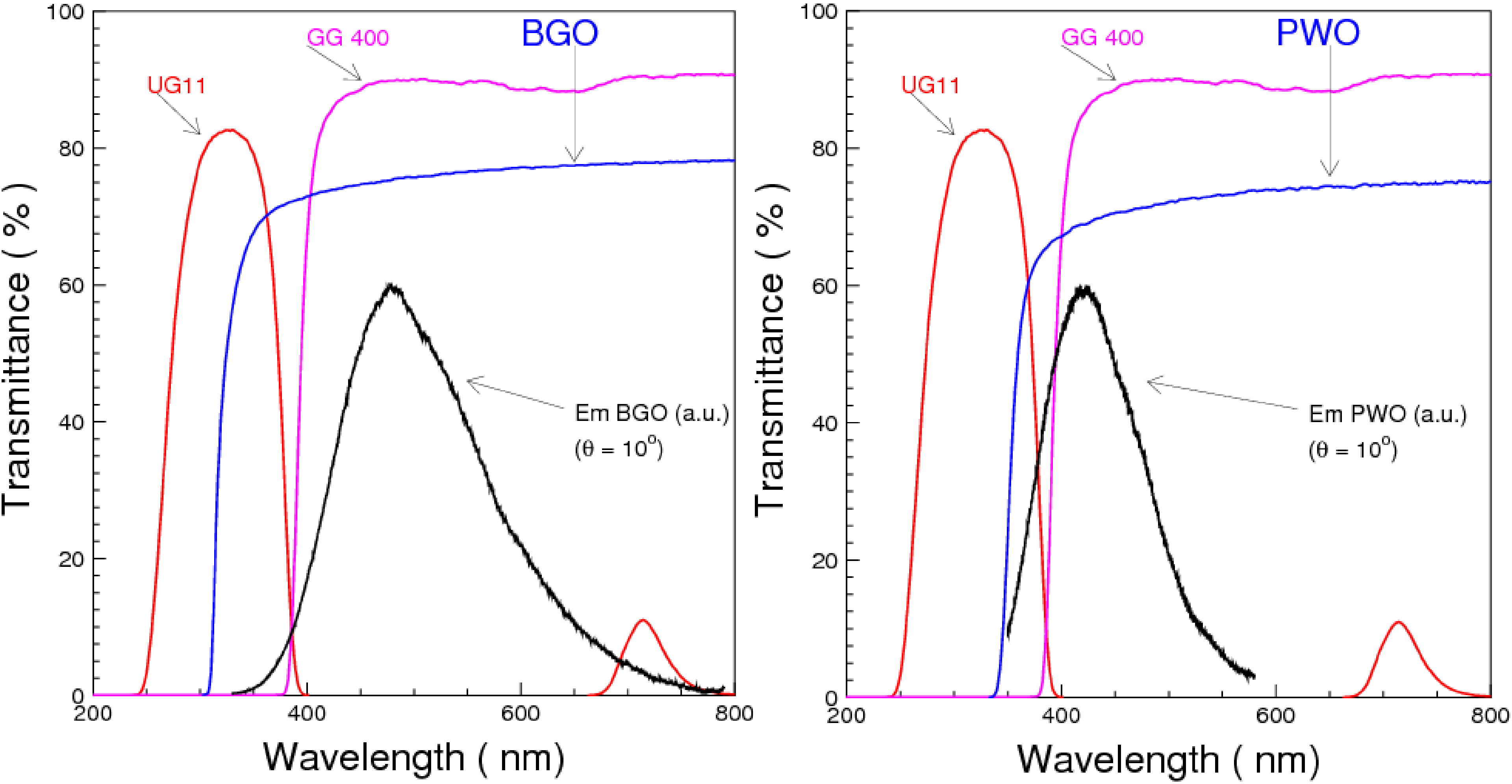


Cherenkov figure of merit

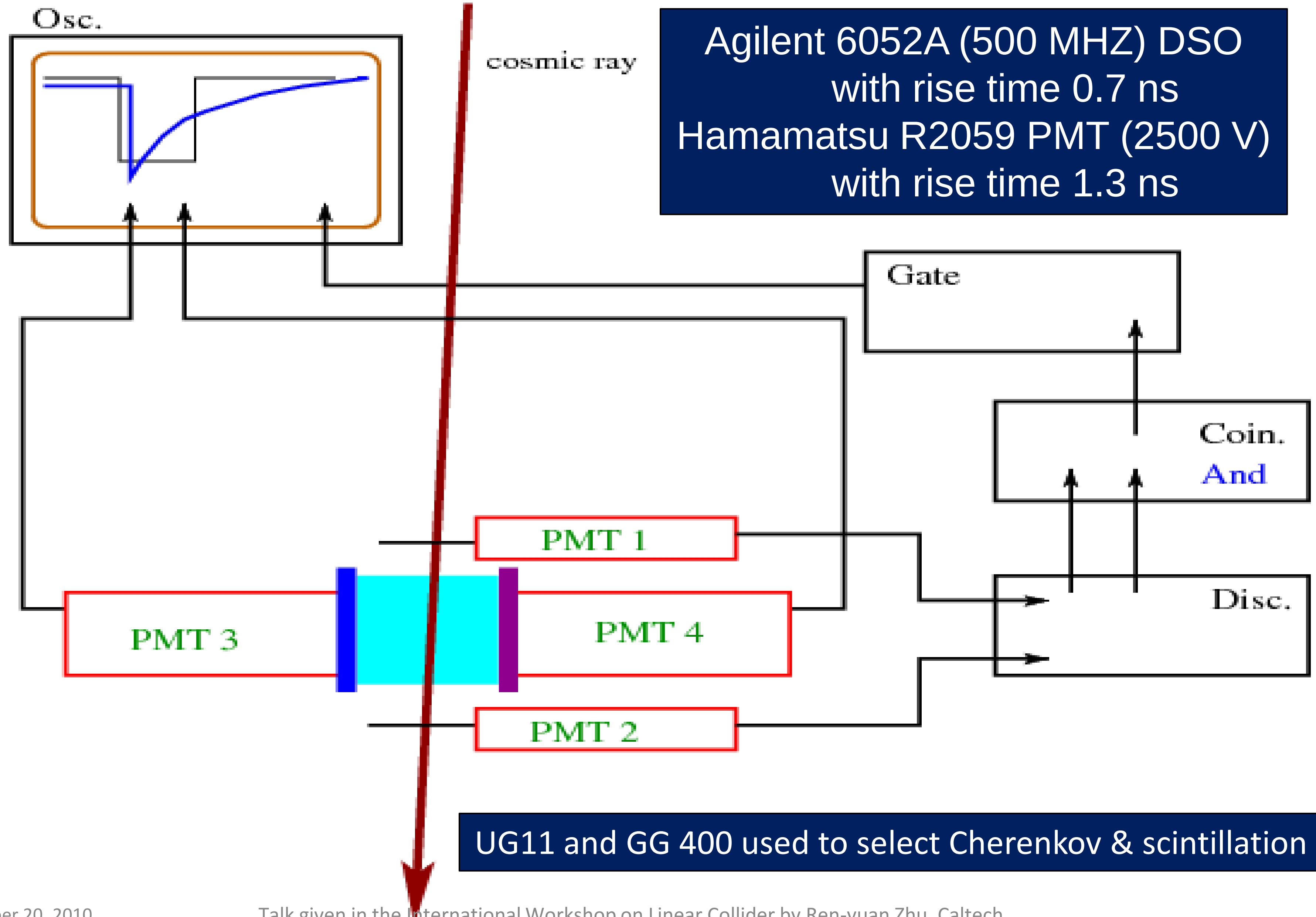
Using UG11 optical filter Cherenkov light can be effectively selected with negligible contamination from scintillation

Scintillation Selected with Filters

UG11/GG400 optical filter effectively selects Cherenkov/scintillation light



Cosmic Setup with Dual Readout

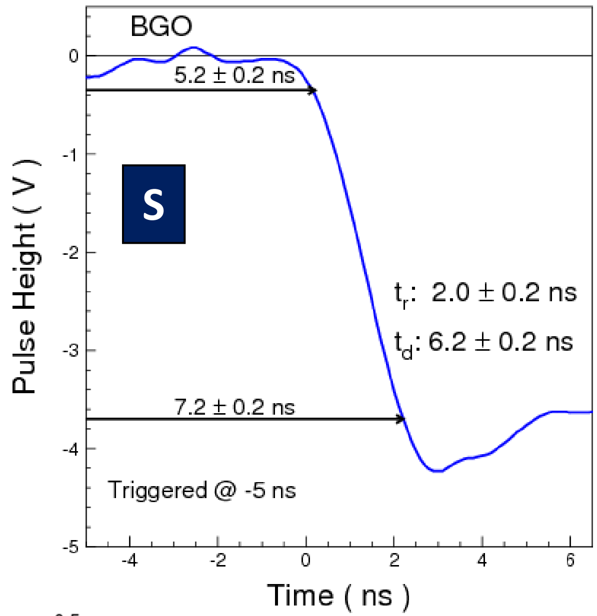


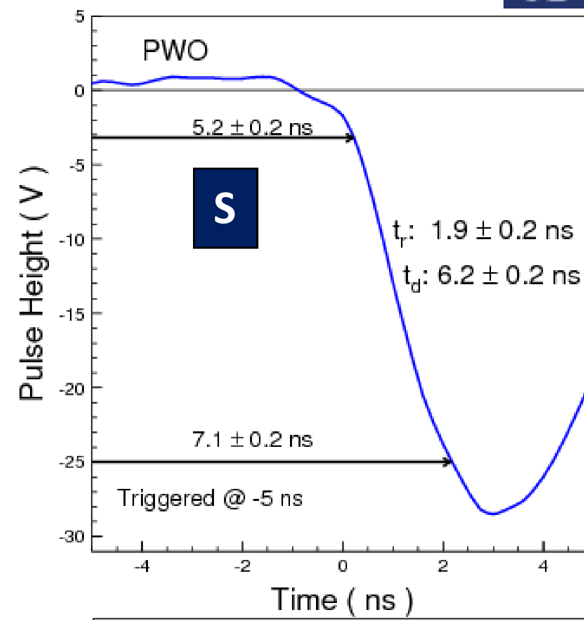
Agilent 6052A (500 MHZ) DSO
with rise time 0.7 ns
Hamamatsu R2059 PMT (2500 V)
with rise time 1.3 ns

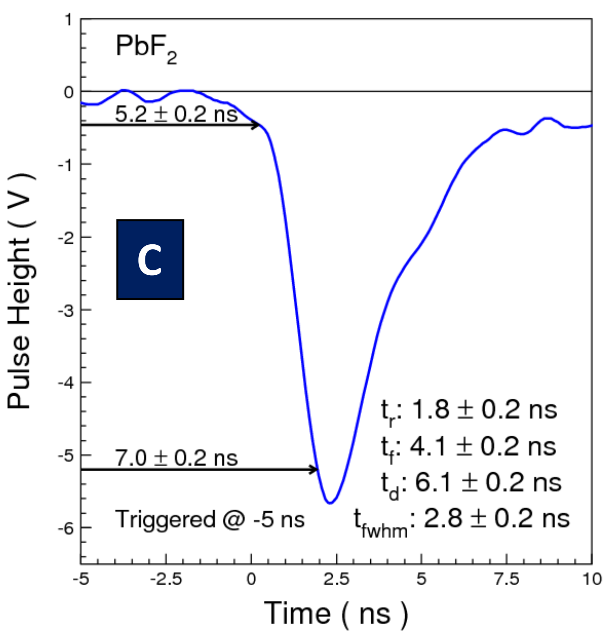
UG11 and GG 400 used to select Cherenkov & scintillation

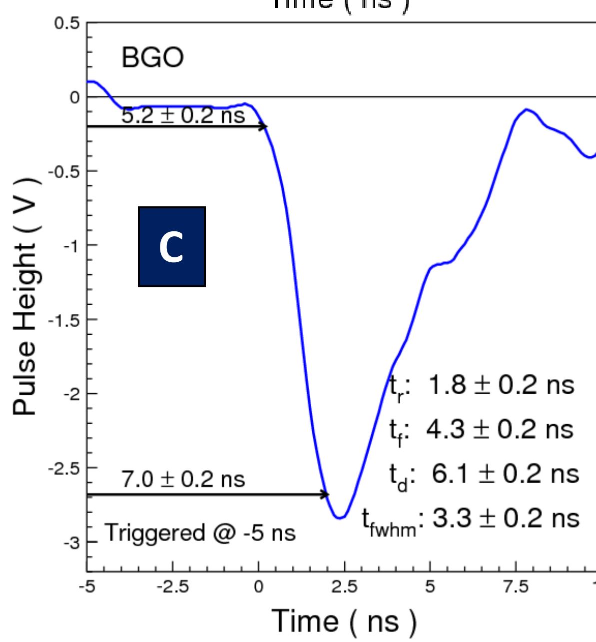
No Discrimination in Front Edge

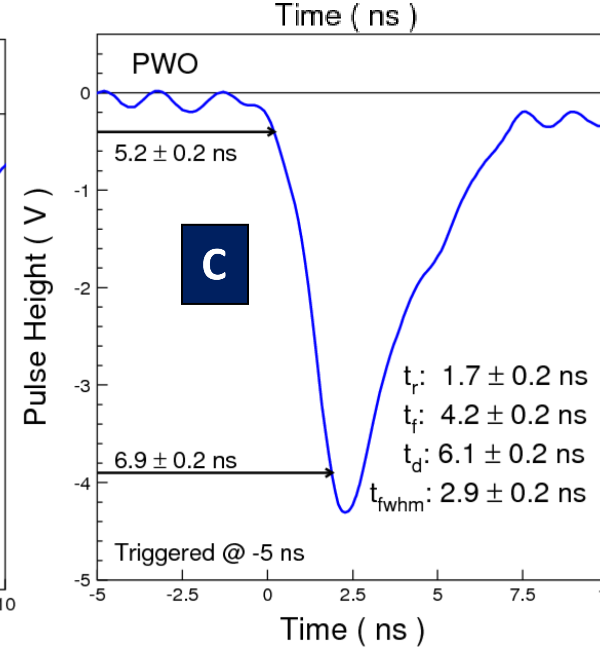
Consistent timing and rise time for all Cherenkov and scintillation light pulses observed.





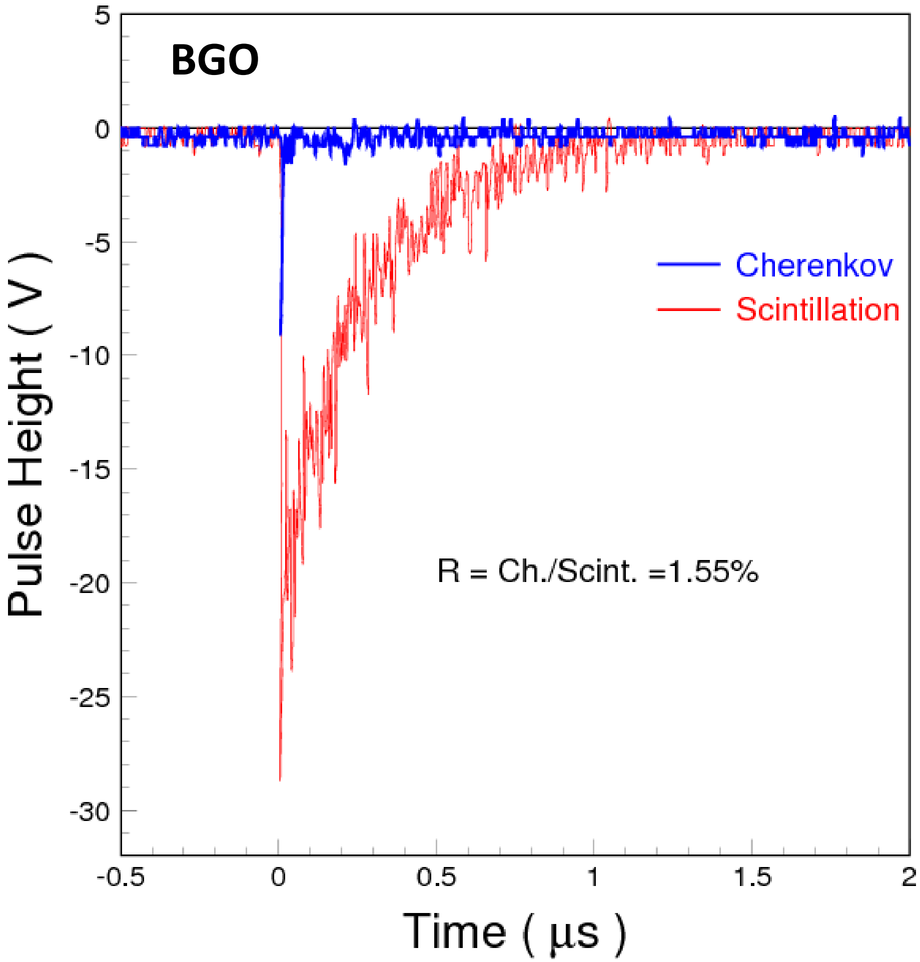


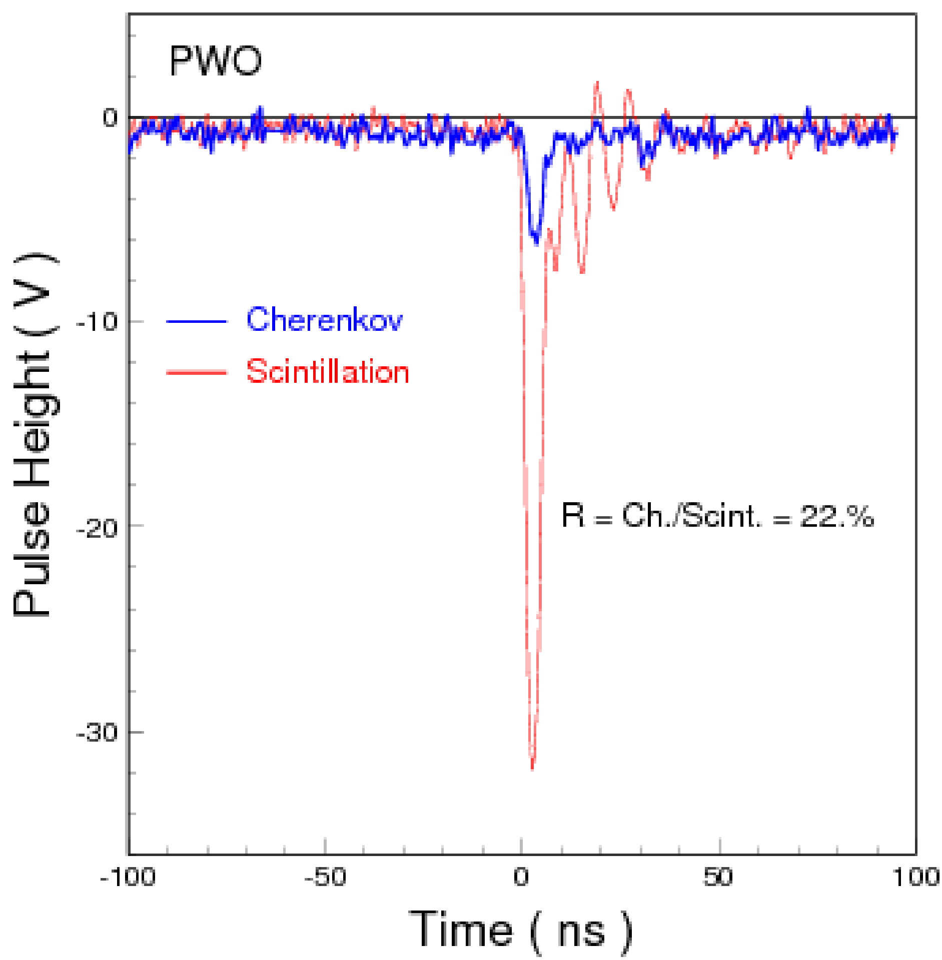




Ratio of Cherenkov/Scintillation

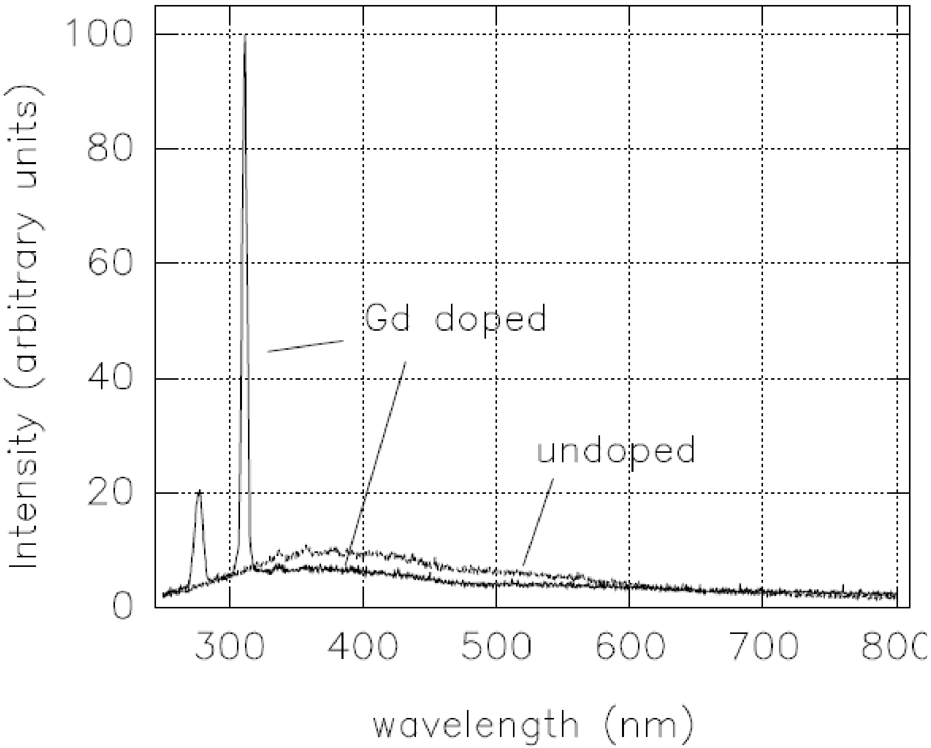
1.6% for BGO and 22% for PWO with UG11/GG400 filter and R2059 PMT, which is configuration dependent.



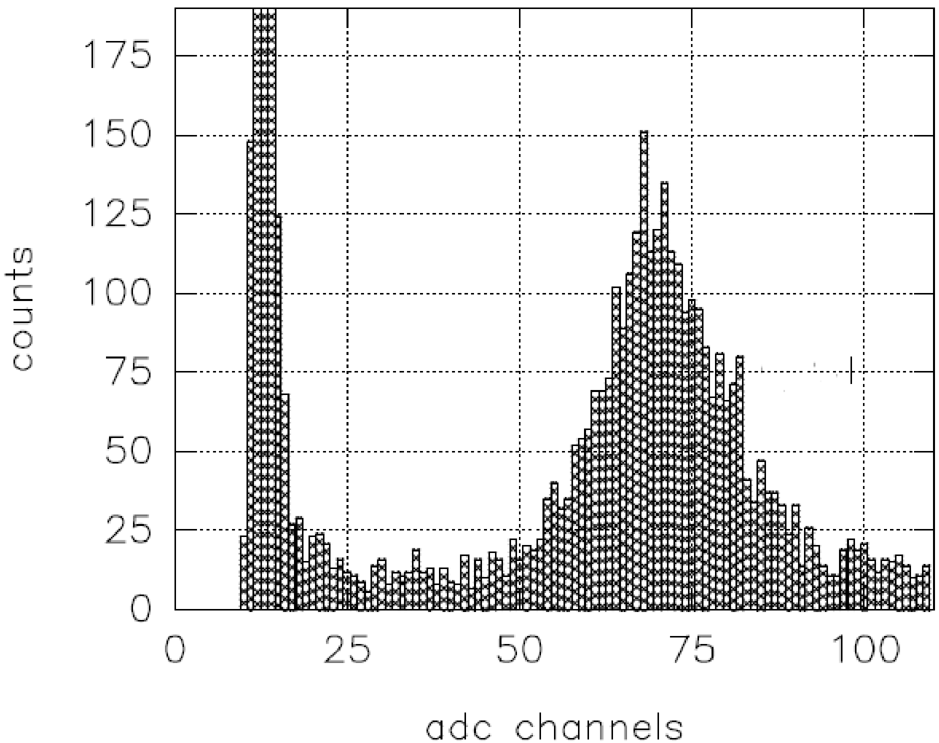


Scintillation was Observed in PbF_2:Gd

Scintillation of PbF_2(Gd)



PbF_2(Gd) Response to MIP of 1 GeV/c

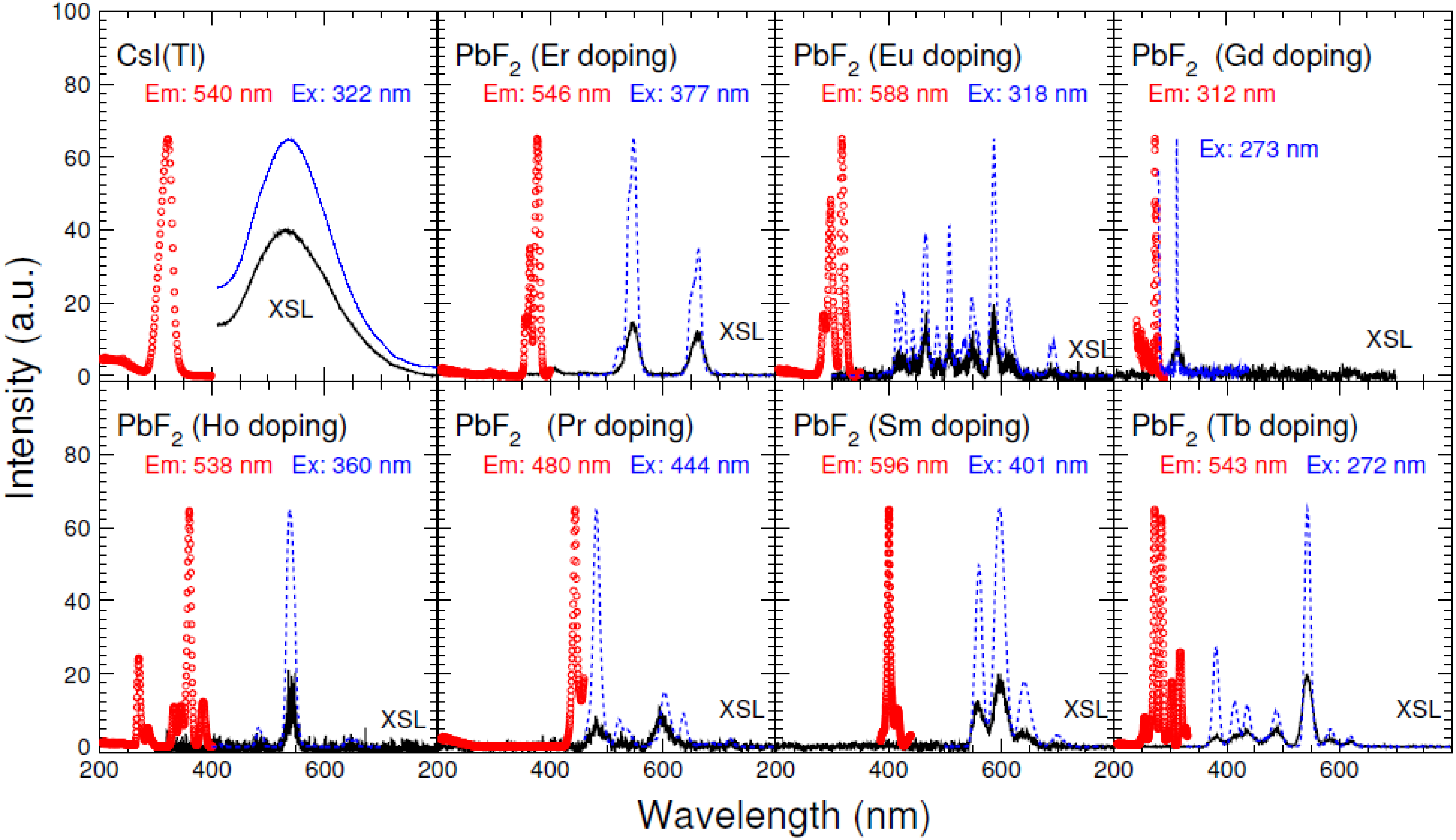


Fast Scintillation of 6.5 p.e./MeV with decay time of less than 10 ns

D. Shen *at al., Jour. Inor. Mater* **Vol. 101** 11 (1995).
C. Woody *et al., IEEE Trans. Nucl. Sci.* ***43*** *(1996) 1303*.

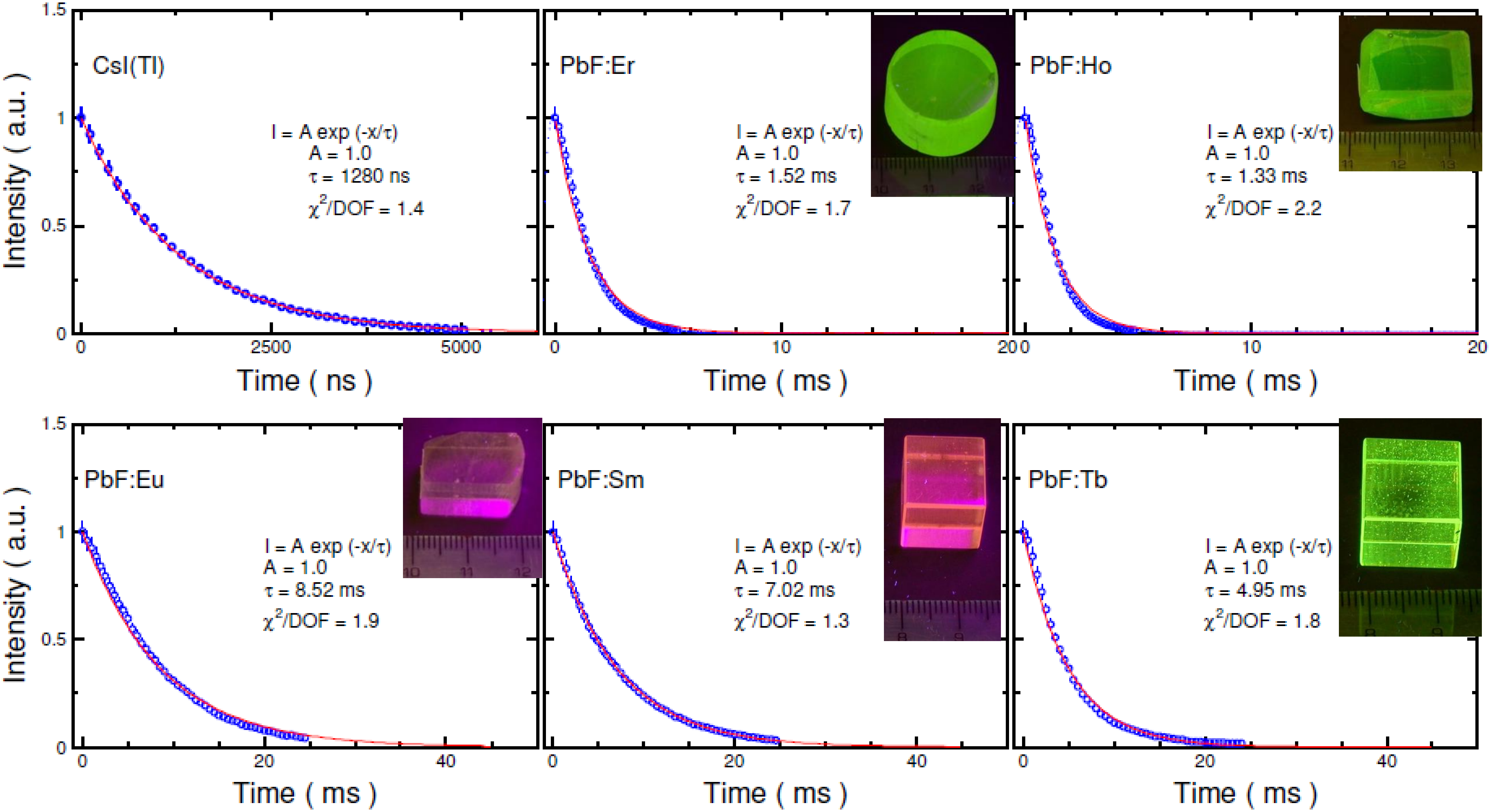
Luminescence Observed in PbF_2

Consistent Photo- and X-luminescence observed in doped PbF_2 samples grown by Prof. Dingzhong Shen of SIC/Scintibow.



Rare Earth Doped PbF_2

Multi-ms decay time observed, which is too slow to be useful.



Summary

- **The HHCAL is an interesting detector concept providing a unprecedented combination of e/ɣ and jet mass resolutions. The crucial issue is to develop high quality materials of low cost: < $2/cc.**
- **Among all crystals, PbF_2, PbClF and BSO seem the best candidates to meet the cost goal.**
- **While consistent photo and x- luminescence was found in Er, Eu, Gd, Ho, Pr, Sm and Tb doped PbF_2 samples, their decay time is at ms scale as expected from the f-f transition of the rare earth elements.**

❑ **The scope of this R&D is now expanded to a broad range other of materials, including BSO, glasses and ceramics etc. See presentations at the 2nd HHCAL Workshop:**

http://indico.ihep.ac.cn/sessionDisplay.py?sessionId=2&slotId=0&confId=1470#2010-05-09

3rd Workshop for the HHCAL

October 31, 2010, at Knoxville just one day before NSS2010

1. A. Para, Prospects for High Resolution Hadron Calorimetry
2. G. Mavromanolakis , Studies on Dual Readout Calorimetry with Meta-Crystals
3. D. Groom, Degradation of resolution in a homogeneous dual readout hadronic calorimeter
4. S. Derenzo, High-Throughput Synthesis and Measurement of Candidate Detector Materials for Homogeneous Hadronic Calorimeters
5. M. Poulain, Fluoride Glasses: State of Art and Prospects
6. I. Dafinei, High Density Fluoride Glasses, Possible Candidates for Homogeneous Hadron Calorimetry
7. P. Hobson, Prospects for Dense Glass Scintillators for Homogeneous Calorimeters
8. G. Dosovitski, Potential of Crystalline, Glass and Ceramic Scintillation Materials for Future Hadron Calorimetry
9. Tianchi Zhao, Study on Dense Scintillating Glasses
10. Jin-tai Zhao, BSO-Based Crystal and Glass Scintillators for Homogeneous Hadronic Calorimeter
11. Guohao Ren, Development of RE-Doped Cubic PbF2 and PbClF Crystals for HHCAL
12, N. Cherepy, Transparent Ceramic Scintillators for Hadron Calorimetry
13. J. Dong, Experimental Study of Large Area GEM
14. H. Frisch, The Development of Large-Area Flat-Panel Photodetectors with Correlated Space and Time Resolution

Spares

Why Crystal Calorimeter?

- Photons and electrons are fundamental particles. Precision e/γ measurements enhance physics discovery potential.
- Performance of crystal calorimeter in e/γ measurements is well understood:
  - The best possible energy resolution;
  - Good position resolution;
  - Good e/ γ identification and reconstruction efficiency.
- Crystals may also provide a foundation for a homogeneous hadron calorimeter with dual readout of Cherenkov and scintillation light to achieve good resolution for hadrons and jets.

Crystal Calorimeters in HEP

Date	75-85	80-00	80-00	80-00	90-10	94-10	94-10	95-20
Experiment	C. Ball	L3	CLEO II	C. Barrel	KTeV	*BaBar*	BELLE	CMS
Accelerator	SPEAR	LEP	CESR	LEAR	FNAL	SLAC	KEK	CERN
Crystal Type	NaI(Tl)	BGO	CsI(Tl)	CsI(Tl)	CsI	CsI(Tl)	CsI(Tl)	$PbWO_4$
B-Field (T)	-	0.5	1.5	1.5	-	1.5	1.0	4.0
r_{inner} (m)	0.254	0.55	1.0	0.27	-	1.0	1.25	1.29
Number of Crystals	672	11,400	7,800	1,400	3,300	6,580	8,800	76,000
Crystal Depth (X_0)	16	22	16	16	27	16 to 17.5	16.2	25
Crystal Volume (m^3)	1	1.5	7	1	2	5.9	9.5	11
Light Output (p.e./MeV)	350	1,400	5,000	2,000	40	5,000	5,000	2
Photosensor	PMT	Si PD	Si PD	WS^a+Si PD	PMT	Si PD	Si PD	APD^a
Gain of Photosensor	Large	1	1	1	4,000	1	1	50
σ_N/Channel (MeV)	0.05	0.8	0.5	0.2	small	0.15	0.2	40
Dynamic Range	10^4	10^5	10^4	10^4	10^4	10^4	10^4	10^5

Future crystal calorimeters in HEP:

PWO for PANDA at GSI

LYSO for a KLOE and SuperB?

Crystals for the HHCAL detector concept?

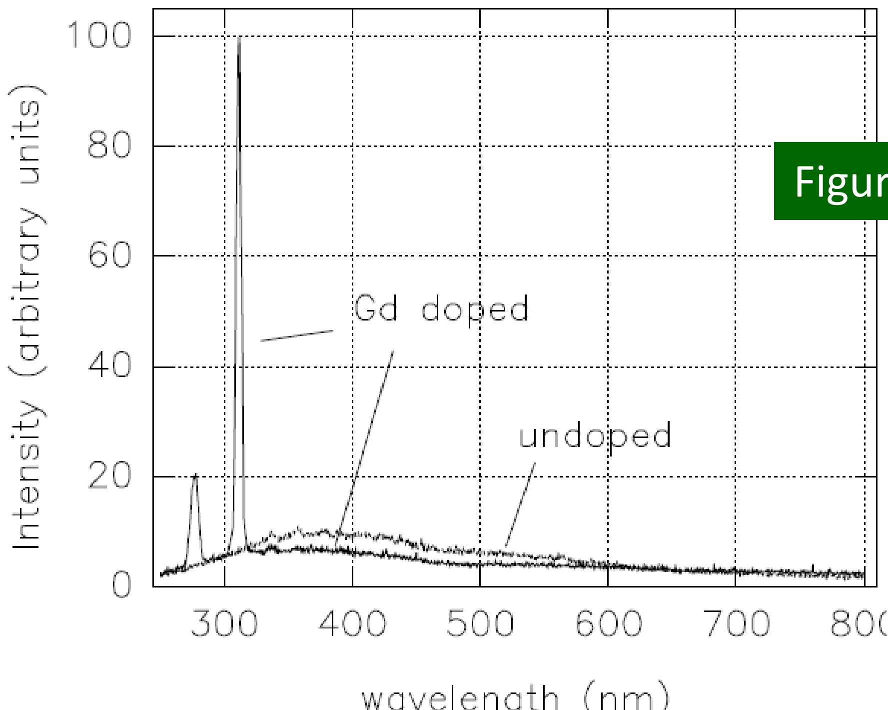
Crystals for HEP Calorimeters

Crystal	NaI(Tl)	CsI(Tl)	CsI	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2
Density (g/cm^3)	3.67	4.51	4.51	4.89	7.13	7.40	8.3	7.77
Melting Point (°C)	651	621	621	1280	1050	2050	1123	824
Radiation Length (cm)	2.59	1.86	1.86	2.03	1.12	1.14	0.89	0.93
Molière Radius (cm)	4.13	3.57	3.57	3.10	2.23	2.07	2.00	2.21
Interaction Length (cm)	42.9	39.3	39.3	30.7	22.8	20.9	20.7	21.0
Refractive Index [a]	1.85	1.79	1.95	1.50	2.15	1.82	2.20	1.82
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Luminescence [b] (nm) (at peak)	410	550	420 310	300 220	480	402	425 420	?
Decay Time [b] (ns)	245	1220	30 6	650 0.9	300	40	30 10	?
Light Yield [b,c] (%)	100	165	3.6 1.1	36 4.1	21	85	0.3 0.1	?
d(LY)/dT [b] (%/ °C)	-0.2	0.4	-1.4	-1.9 0.1	-0.9	-0.2	-2.5	?
Experiment	Crystal Ball	BaBar BELLE BES III	KTeV	(L*) (GEM) TAPS	L3 BELLE	SuperB	CMS ALICE PANDA	HHCAL?

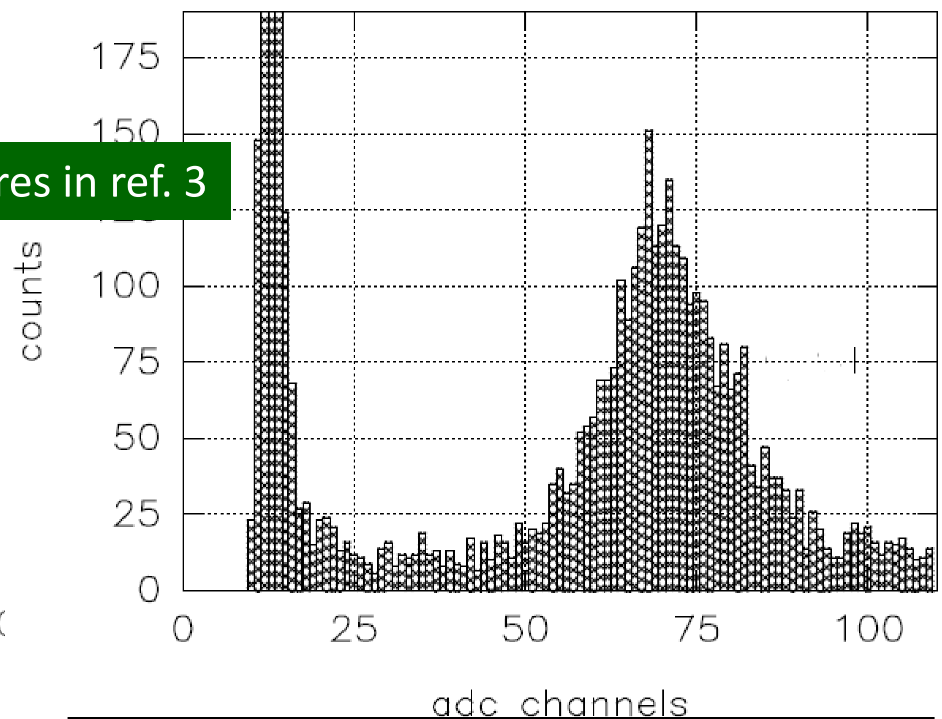
a. at peak of emission; b. up/low row: slow/fast component; c. QE of readout device taken out.

Scintillation of PbF_2 at Room T

1. **Deformation and thermal treatment application to heavy scintillators production,** S.N. Baliakin et. Al., proceedings of SCINT1992, Chamonix, France, Sept. 22-26 (1992) 587.
2. **A search for scintillation in doped and Othrorhombic lead fluoride,** D.F. Anderson, J.A. Kierstead, P. Lecoq, S. Stoll, C.L. Woody, NIM **A342**, (1994) 473.
3. **Observation of fast scintillation light in a PbF_2:Gd crystal**, C. Woody, S. Stoll, J. Kierstead, IEEE TNS, **43** (1996) 1303.



Figures in ref. 3

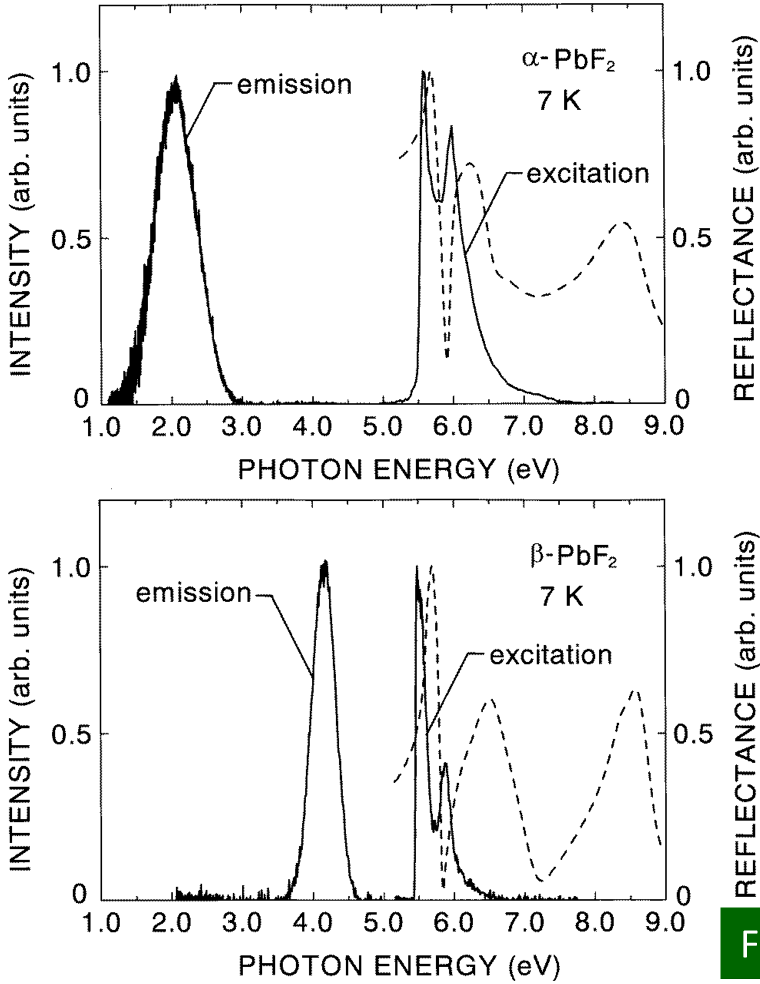


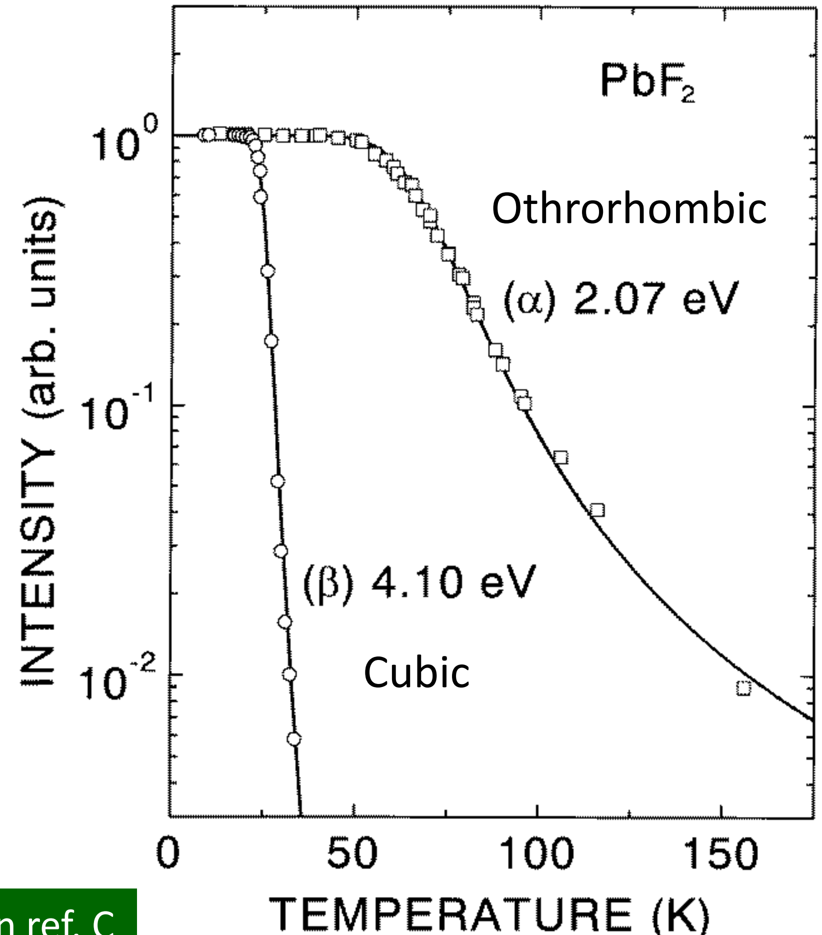
Radio luminescence of PbF_2(Gd)

PbF_2(Gd) Response to MIP of 1 GeV/c

Luminescence of PbF_2 at Low Temperature

A. **Luminescence Kinetics of PbF_2 Single Crystals ,** M. Nikl, K. Polak, Phys. Status Solidi **A117** (1990) K89.
B. **Luminescence of orthorhombic PbF_2**, D. L. Alov, S. I. Rybchenko, J. Phys.: Condens. Matter **7** (1995) 1475.
C. **Photoluminescence of orthorhombic and cubic PbF_2 single crystal**, M. Itoh, H. Nakagawa, M. Kitaura, M. Fujita, D. Alov, J. Phys.: Condens. Matter **11** (1999) 3003.





Figures in ref. C

PbF_2 Samples Tested

- A total of 116 samples with various rare earth doping were grown by vertical Bridgman method at SIC and Scintibow.
- SIC samples: grown in **platinum** crucible, 1.5 X_0 (14 mm) cube.
- Scintibow samples: grown in **graphite** crucible, Φ 22 x 15 mm.

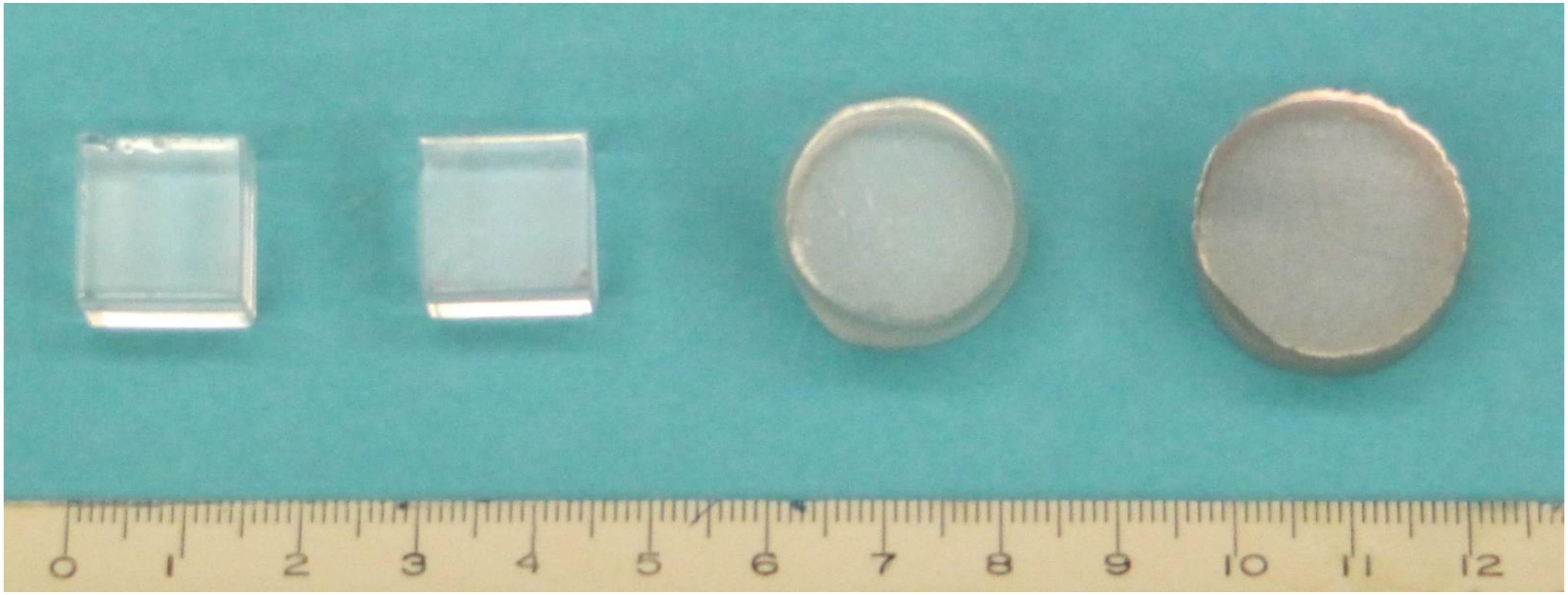
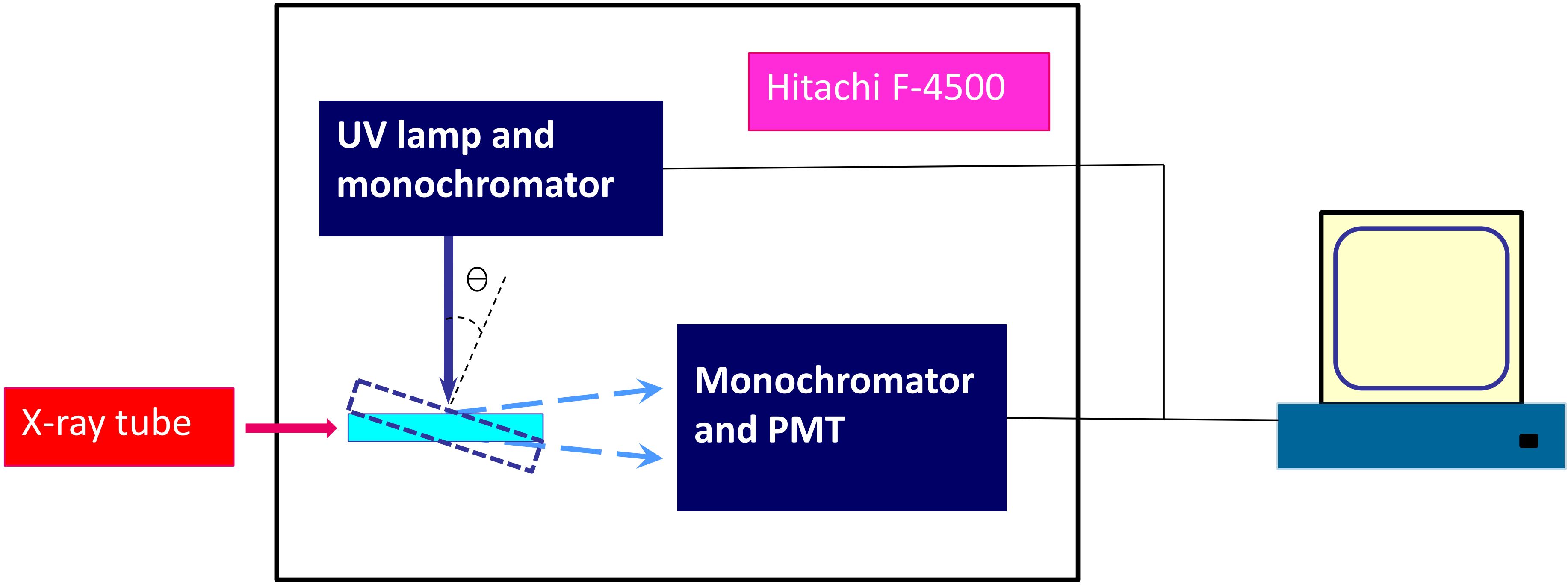
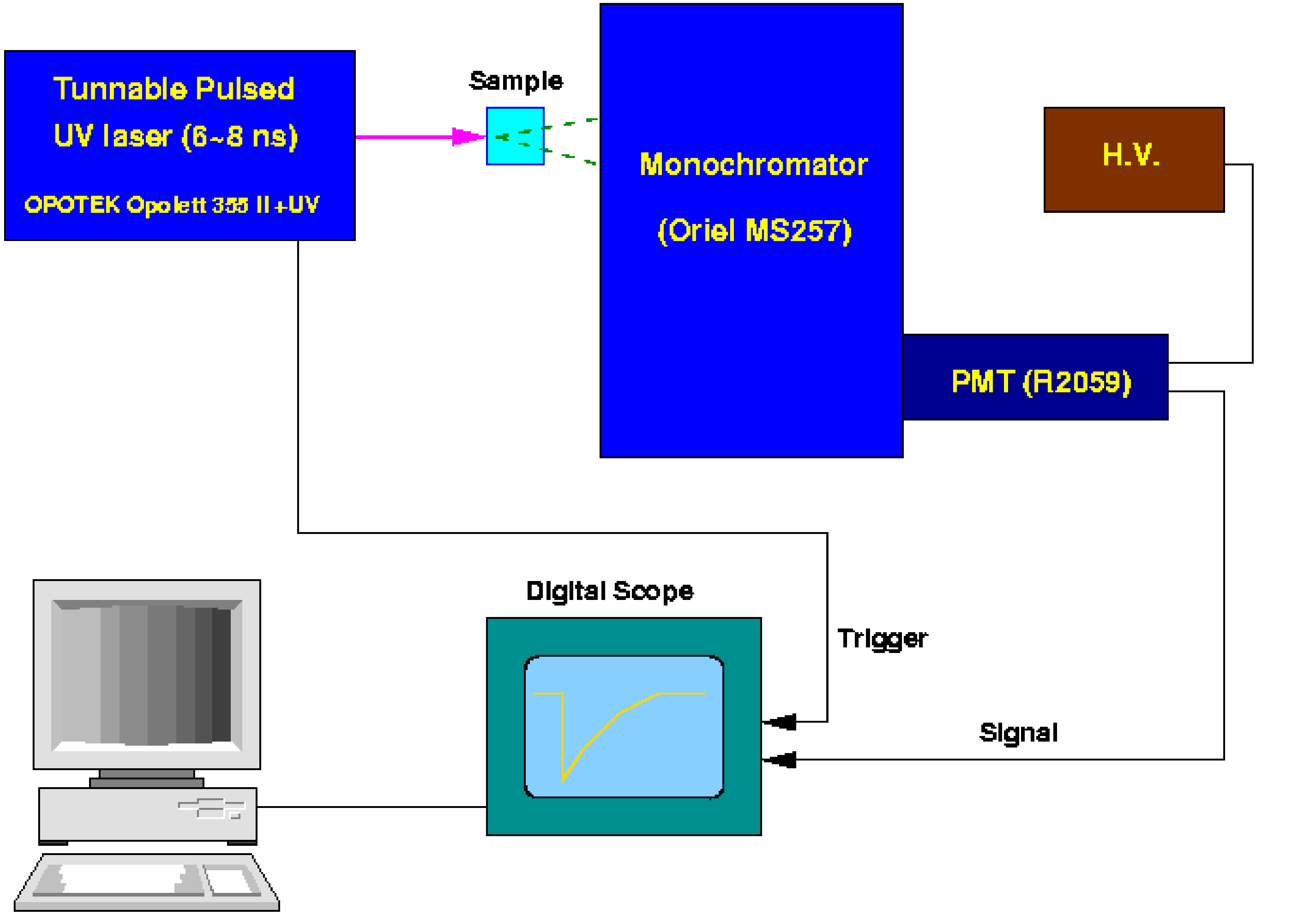


Photo- and X-luminescence

- Photo luminescence was measured by using Hitachi F-4500 fluorescence spectrophotometer.
- An AMTPEK portable X-ray tube was used for the X-luminescence measurement.



Decay Time Measurement



Comparison with the Ref. 2

No fast luminescence of d-f transition was observed

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Table 1
Properties of doped, cubic PbF_2 crystals

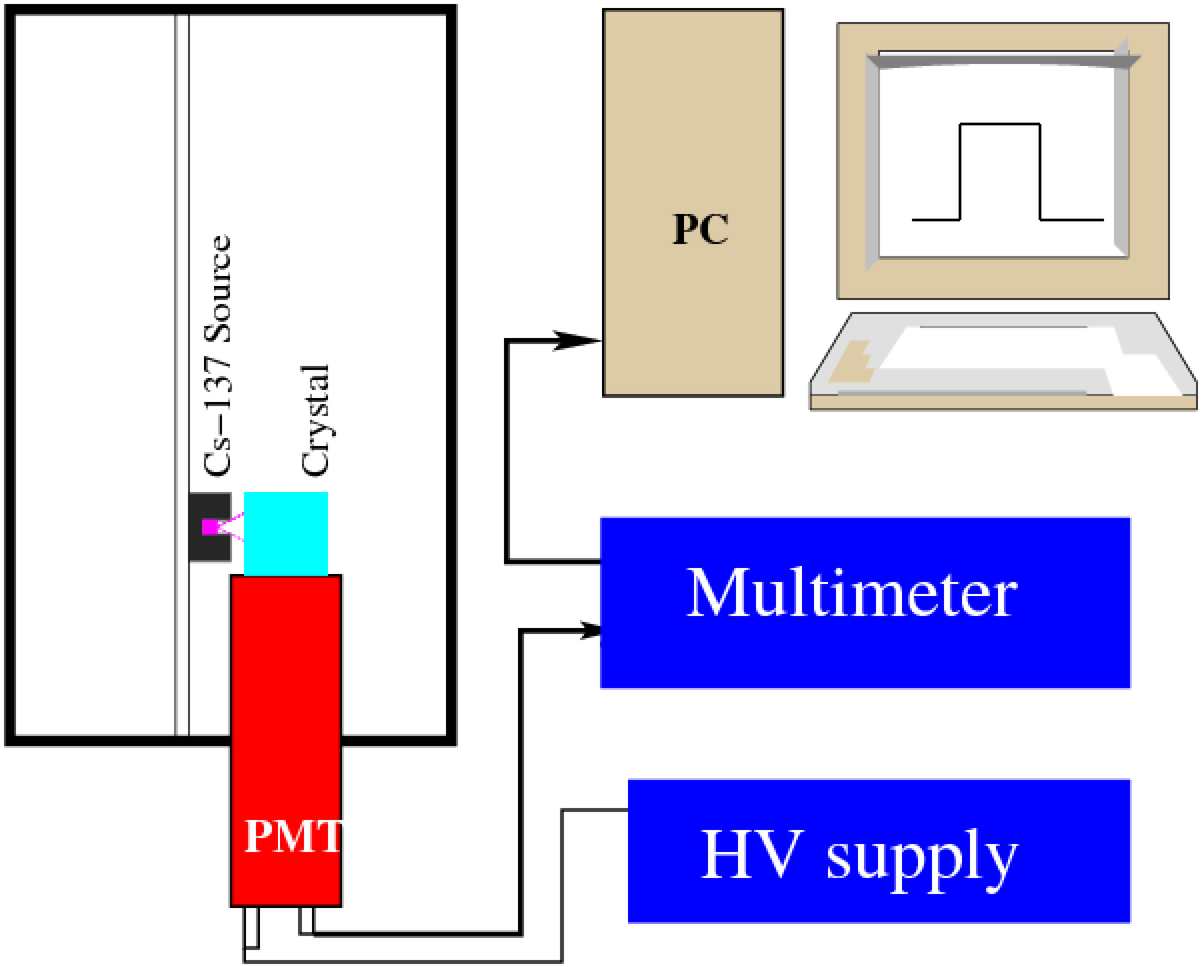
Producer	Dopant [a]	Band-edge	Luminescence
Optovac, Inc.	none	260 nm	no
Optovac, Inc.	Ba	330 nm	weak 358 nm
Optovac, Inc.	Tb	260 nm	slow 384, 414, 434, 487, 542 nm
Optovac, Inc.	Bi	260 nm	no
Optovac, Inc.	Co	350 nm	no
Optovac, Inc.	Ag	260 nm	no
Optovac, Inc.	Cu	305 nm	no
Optovac, Inc.	Cr	260 nm	no
Optovac, Inc.	Dy	260 nm	slow 448 nm, 512 nm,
Optovac, Inc.	Sm		slow 564, 594, 600 nm
Optovac, Inc.	Yb		weak 405 nm
Optovac, Inc.	Eu		slow 467, 510, 589, 619 nm
Optovac, Inc.	Nd 0.5%		no
Optovac, Inc.	Ho 0.5%		no
Optovac, Inc.	Er0.5%		no
Optovac, Inc.	Tm0.5%		no
S.I.C.	none	260 nm	no
S.I.C.	Ce 100 ppm	315 nm	no
S.I.C.	Ce	325 nm	no
S.I.C.	Ba 10% Ce 0.1%	325 nm	no
S.I.C.	Ba 20%	315 nm	no
Ce	0.1%		
S.I.C.	Ce	325 nm	no
S.I.C.	Ce	325 nm	no

[a] All dopants without concentrations are 1%.

Dopant	Caltech	Ref-2
Sm	f-f	f-f
Eu	f-f	f-f
Tb	f-f	f-f
Tm	no	no
Ce	no	no
Nd	no	no
Ho	f-f	no
Er	f-f	no
Dy	no	f-f
Yb	no	f-f?
Pr	f-f	N/A
Gd	f-f ?	N/A

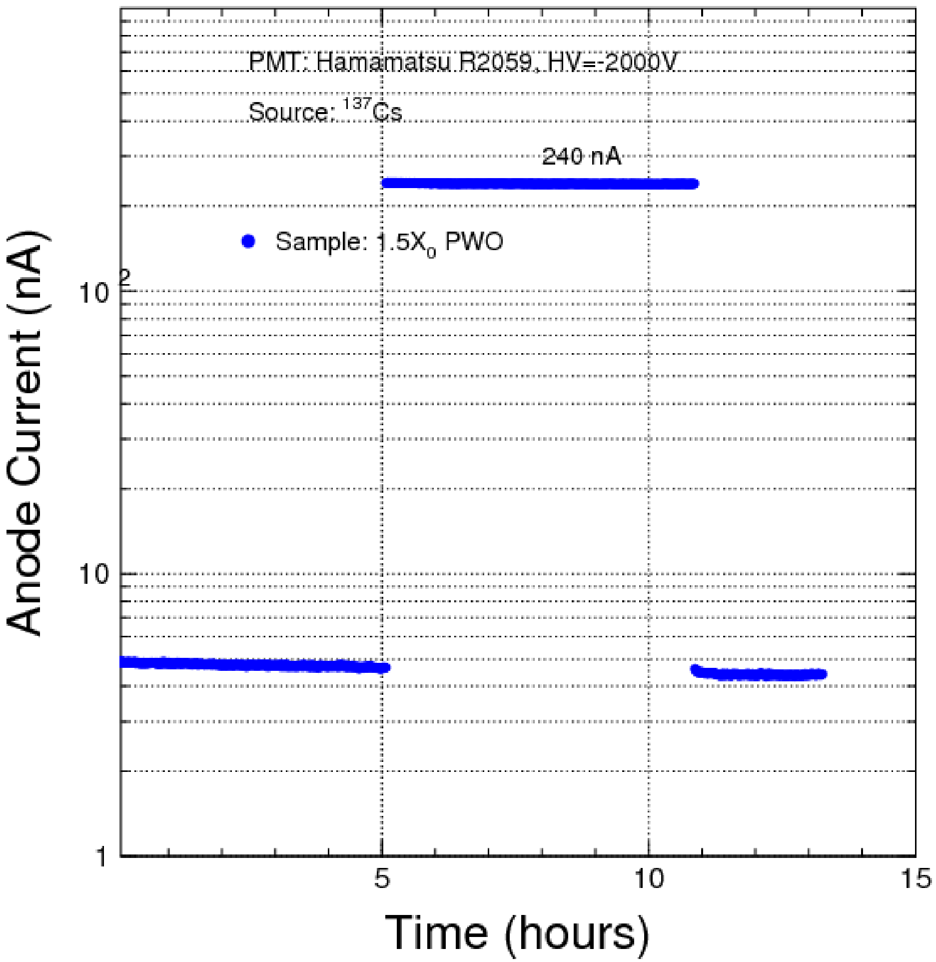
Anode Current Measurement

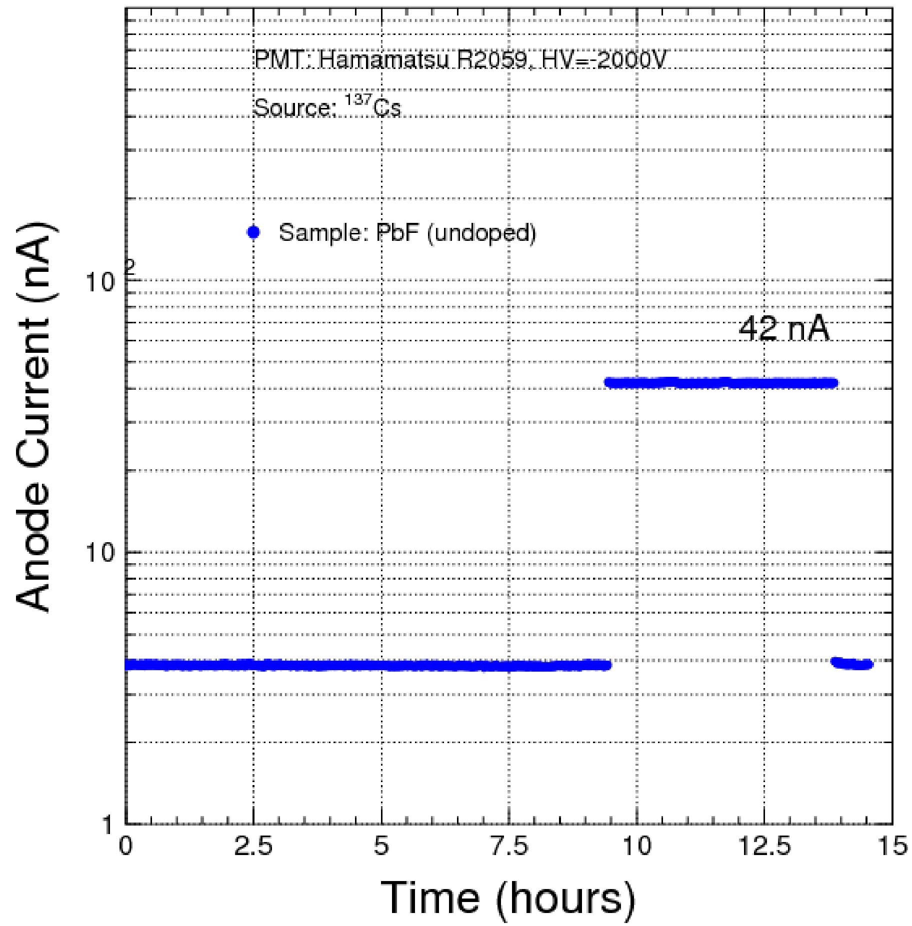
Distance between source and sample: 2 cm



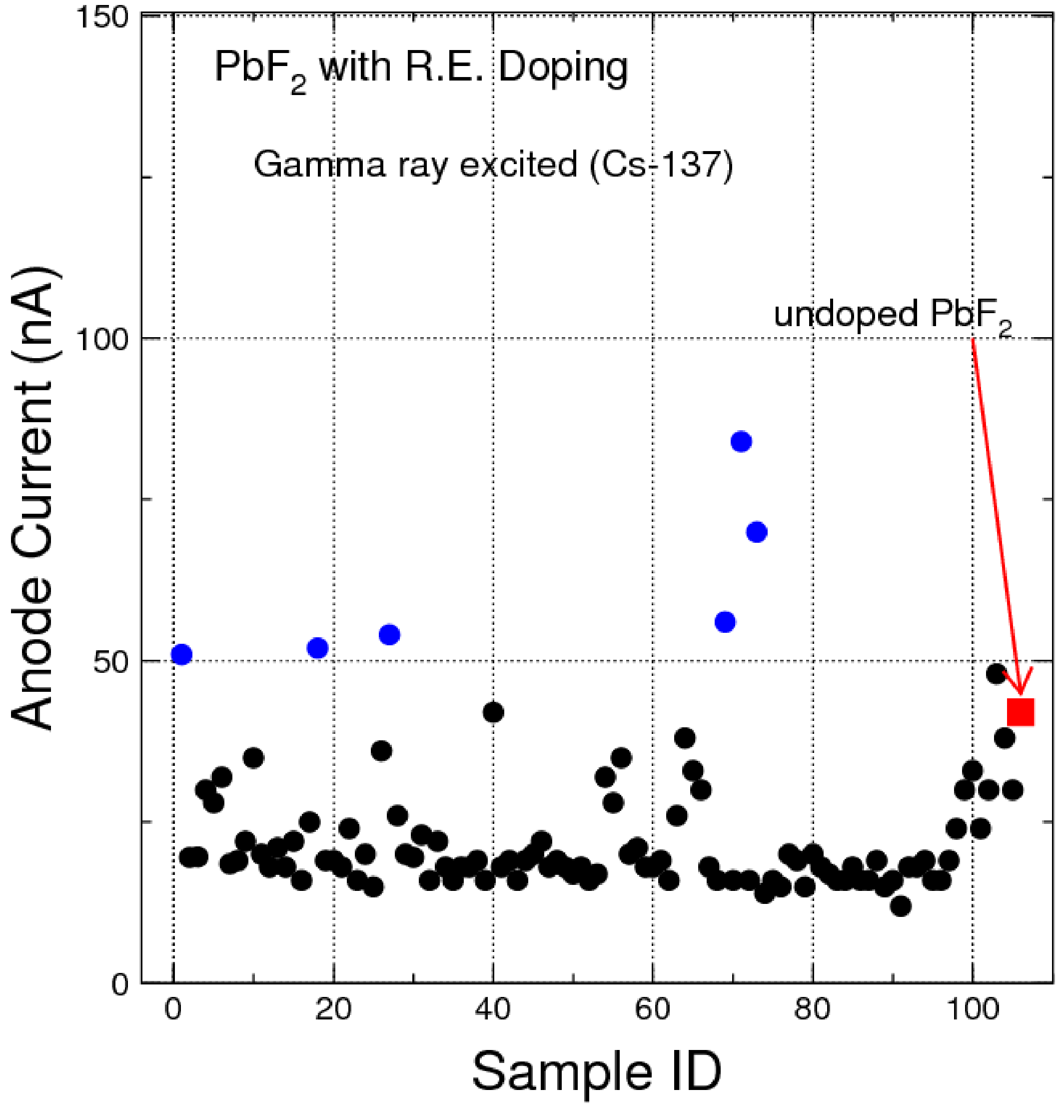
Anode Current: PWO & Un-doped PbF_2

PWO: L.O. = 20 p.e./MeV, anode current = 240 nA





Anode Current: All Samples



Summary of Anode Current

ID	Anode current (nA)	Size (mm)	Doping
Scintibow-1	51	18 x12 x10	Eu
Scintibow-18	52	Φ22X15	Eu/Gd
Scintibow-27	53	Φ20X15	Eu/Tb
Scintibow-B19	56	Φ20X15	Eu/Tb/Na
Scintibow-B21	83	Φ22X15	Eu/Bi/Na
Scintibow-B23	73	Φ20X15	Eu/Bi/Na
Undoped	42	14 x 14 x14	--