$PbWO_4$ Specs and QA

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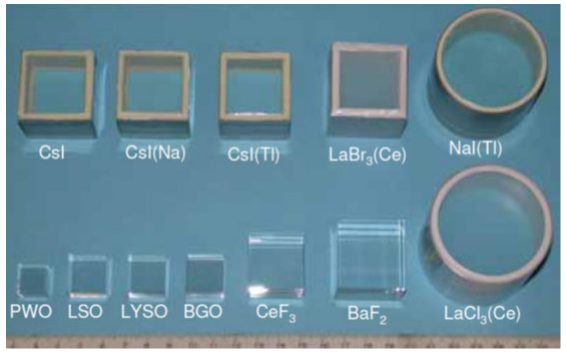
Context for $PbWO_4$ Specifications



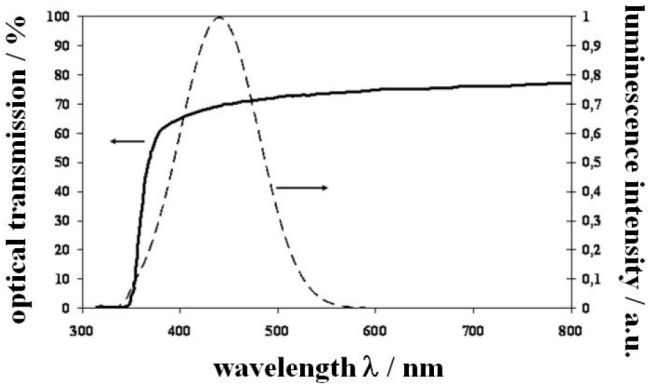
In general, for high-precision electromagnetic calorimetry, the following are of relevance:

- Smaller radiation length for smaller longitudinal size
- Smaller Moliere radius allowing higher granularity
- Smaller decay time
- Better energy resolution. Larger number of photoelectrons per MeV to reach higher resolution
- Smaller constant term contribution to energy resolution, mainly due to non-uniformity and gaps, to readout and noise. → for sensitivity checks need tests with detector prototypes in beam
- Reasonable temperature dependence to light yield
- Higher radiation hardness (EM and/or hadron fluences)

Parameter ======= Material	Density (g/cm^3)	Rad. Length (cm)	Moliere Radius (cm)	Decay time (ns)	Light Yield (γ/MeV)	dLY/dT (%/°C)	Rad. Hard. (krad)
NaI(Tl)	3.67	2.59	4.13	245	41000	-0.2	1--2
CsI(Tl)	4.51	1.86	3.57	1220	60000	0.4	1
CsI	4.51	1.86	3.57	35 6	1600 400	-0.6 -1.4	1
BaF_2	4.89	2.03	3.1	650 0.9	16000 2000	-1.9 0.1	>50
CeF_3	6.16	1.70	2.41	30	2800	~0.1	>100
(BGO) $Bi_4Ge_3O_{12}$	7.13	1.12	2.23	300	8000 4000	-0.9 -1.6	>1000 (recovery
(PWO) $PbWO_4$	**8.3**	**0.89**	**2**	**30 10**	**40 240**	**-2.5**	**>1000**
SciGlass	3.7-4.5	2.2-2.8	2--3	20-50	500-2000	None	>1000

$PbWO_4$ meets the requirements of an extremely fast, compact, and radiation hard scintillator material providing sufficient luminescence yield to achieve good energy resolution.

$PbWO_4$ Specifications

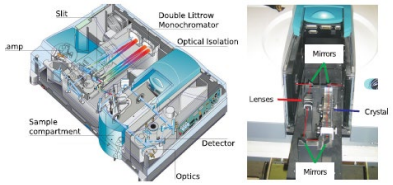
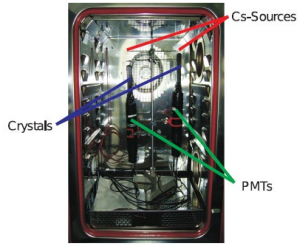
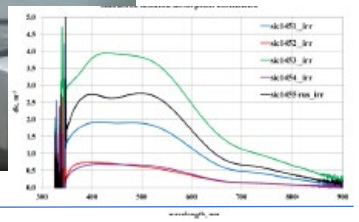
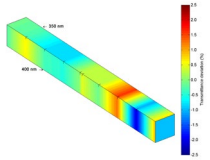
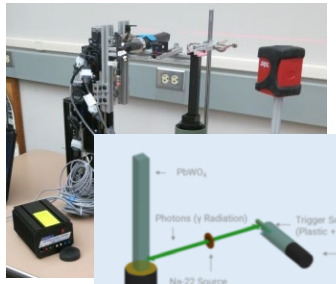
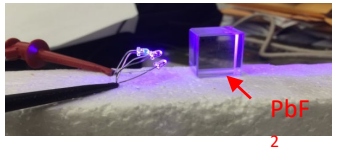
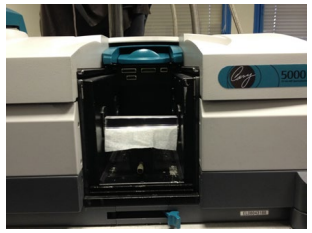
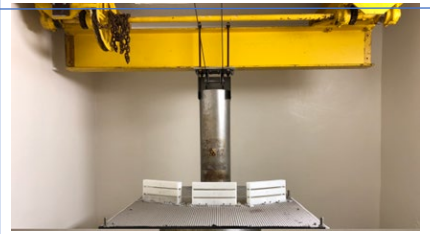
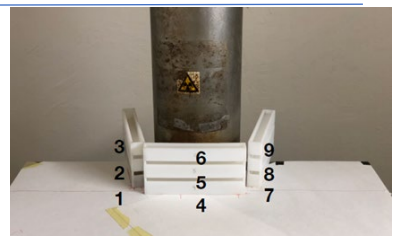
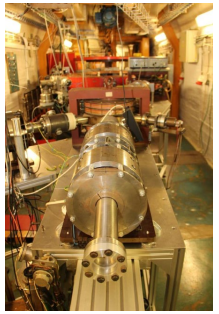
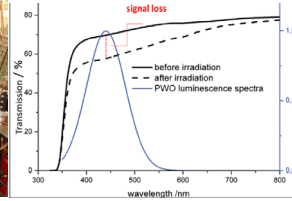


- Smaller decay time – fast timing
  - LY (100ns)/LY(1us) specification
- Optimizing the light yield relies on crystal transmittance in the near UV region
  - longitudinal transmittance specification
  - Transmittance spectrum in agreement with photosensor curve
- Require homogeneous collection of scintillation light along the crystal
  - specification on transverse transmittance
- Mechanical specifications important for assembly, e.g., to minimize gaps
- Raw materials used impact crystal performance – QA with vendor

$PbWO_4$ specifications are similar to those achieved for JLab Projects (NPS, FCAL)

Parameter	Unit	EEEMCAL Required	Q&A Inform. Source
Light Yield (LY) at RT (for all sides polished crystals)	pe/MeV	≥15	Test with γ-source
LY(100ns)/LY(1μs)	%	>90	Test with γ-source
Longitudinal Transmission at λ=360 nm at λ=420 nm at λ=620 nm	 % % %	 ≥35 ≥60 ≥70	Optical Measurement
Transverse Transmission and LY uniformity along crystal	%	10	Optical Measurement
Inhomogeneity of Transverse Transmission Δλ at T=50%	nm	≤5	Optic. Measure.
Induced radiation absorption coefficient Δk at λ=420 nm and RT, for integral dose >100 Gy	m^{-1}	<1.5	Irradiate with different sources
Mean value of dk	m^{-1}	≤1.0	Test
Tolerance in Length Tolerance in sides	μm μm	≤±0,-100 ≤±50	Measure.
Surface polished, roughness Ra	μm	≤0.02	Vendor
Tolerance in Rectangularity (90°)	degree	≤0.1	Measure.
Purity specific. (raw material)			Vendor
Mo contamination	ppm	<10	Vendor
La, Y, Nb, Lu contamination	ppm	?	Vendor

QA facilities at Universities

	Optical Transmittance (L/T)	Crystal light yield and timing	Radiation Hardness and recovery
JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN	 Modified Varian Cary 5000 spectrometer	 Cs-137 source and calibrated 2-inch PMT (Hamamatsu R2059-01) with QE(420nm)=24%.	 Co-60 sources 
THE CATHOLIC UNIVERSITY OF AMERICA	  Perkin-Elmer Lambda 950 spectrometer	  Na-22 source and 2-inch PMT (XP2262)	  x-ray irradiation system (Faxitron CP-160)
IJCLab Irène Joliot-Curie	 Varian Cary 5000 spectrometer	 Cs-137 source and 2-inch PMT	  Co-60 source, 222 TBq, simultaneous irradiation of nine crystals/water; different dose rates possible
CHARLES UNIVERSITY			   Electrons 5.5 MeV < E_e < 16.6 MeV; adjust beam intensity to illumination with g rays (Co-60, 30 Gy)

JLab crystal test facility for $PbWO_4$ QA and prototype

Jefferson Lab
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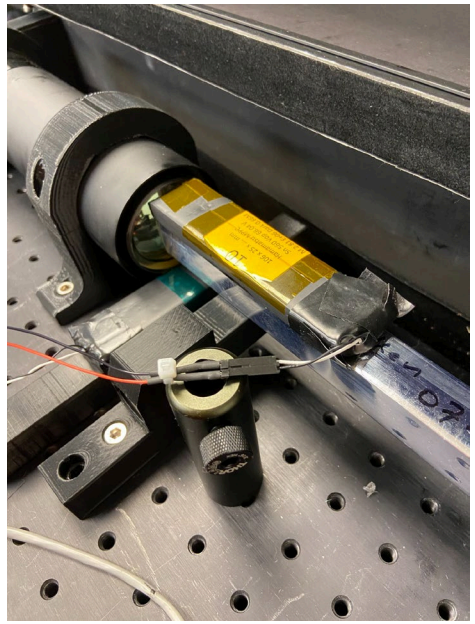
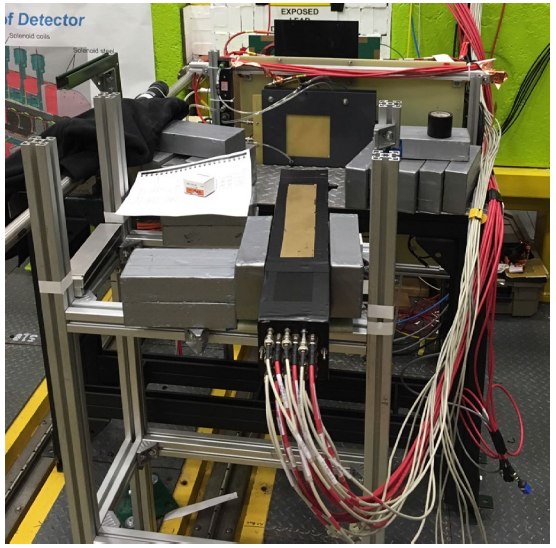
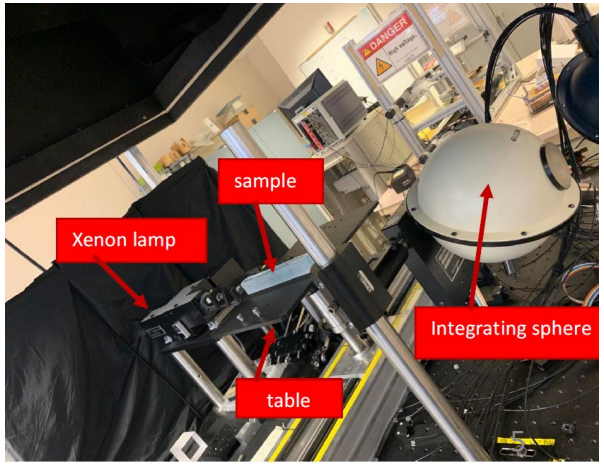
- Dedicated cleanroom facility for crystal characterization
  - Mitutoyo QM - for mechanical dimensions measurements. Precise to 1 micron.
  - Crystal Light Yield measurements
  - Optical transmittance with integrating sphere
  - Radiation hardness in beam
- Beam test facility with tagged photon beam up to 4-5 GeV
  - Technique demonstrated successfully for NPS can be adapted for EIC prototype tests

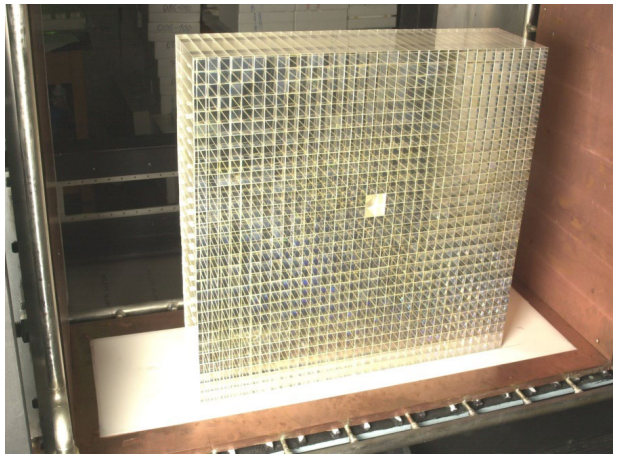


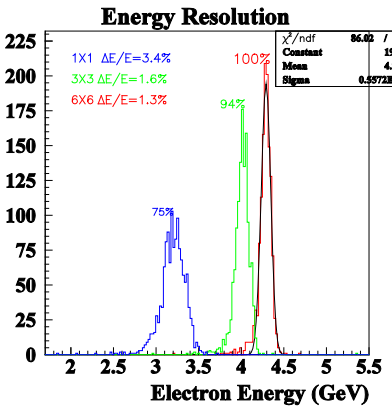


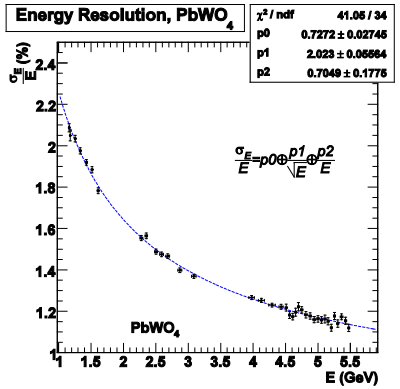


Crystal Prototype Beam Test Campaigns at JLab

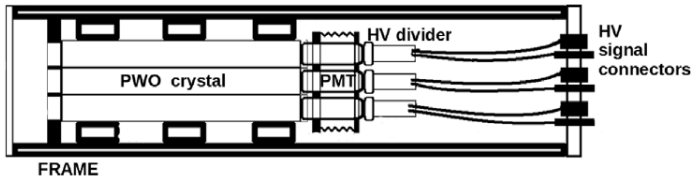
HyCal (pre-2014)
1152 $PbWO_4$ crystals (PWO-I)
SICCAS/China

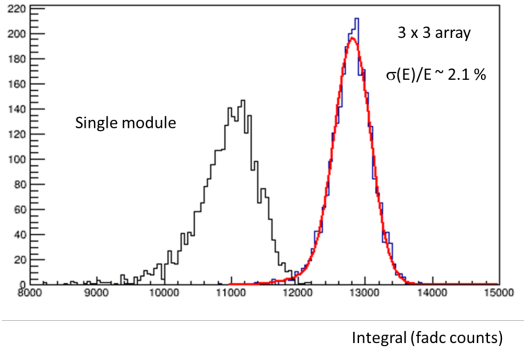






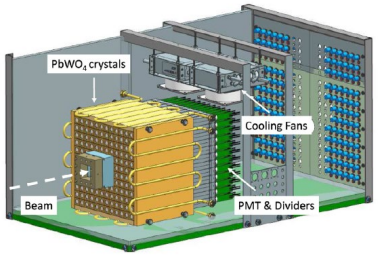
3x3 prototypes (2018/19)
9 $PbWO_4$ (PWO-II) crystals
CRYTUR/Czech Rep.

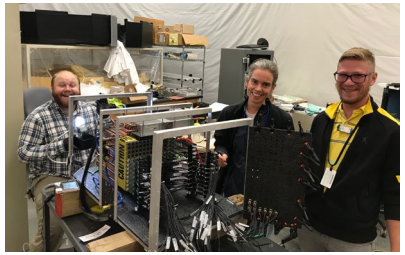


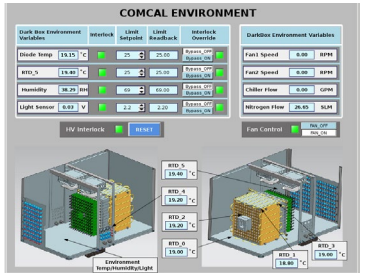


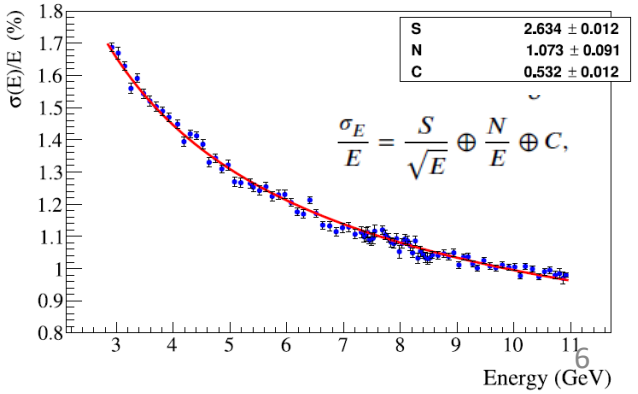
12x12 prototypes (2019)
144 $PbWO_4$ (PWO-II) crystals
CRYTUR/Czech Rep/

ComCal/
FCAL





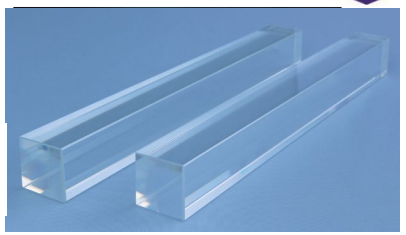




$PbWO_4$ crystal production for JLab Projects

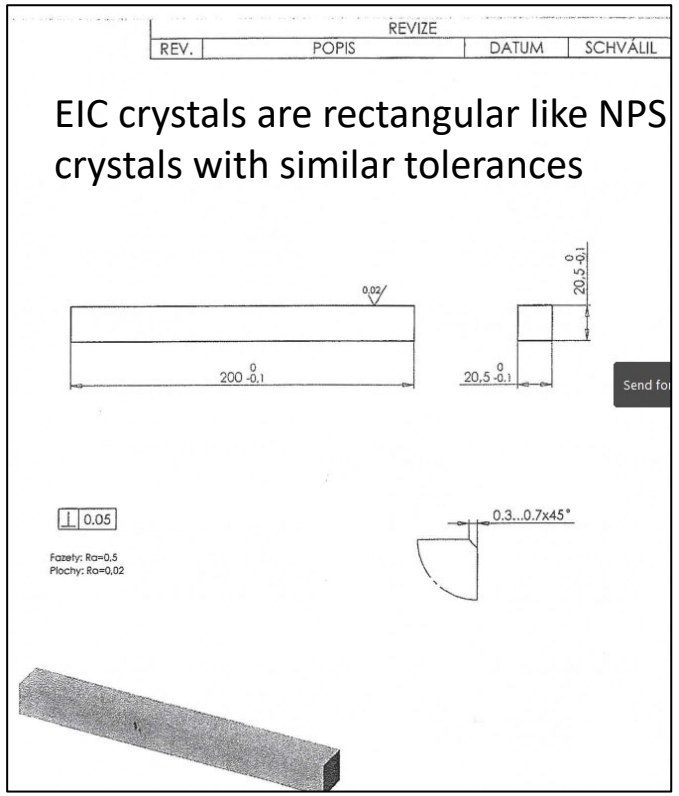
Production of PWO crystals at CRYTUR – Turnov, Czech Republic

- long tradition in the production of inorganic scintillators. Restart of PWO production in 2014
  - production based on Czochralski technology



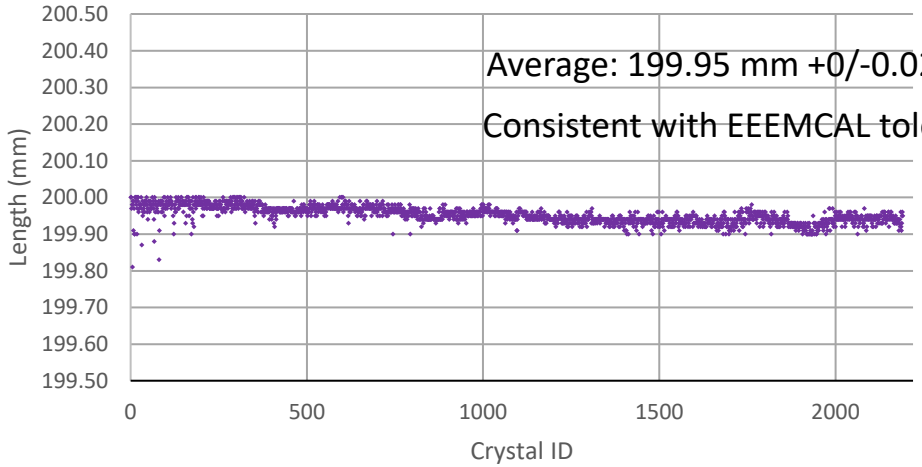
- ~2190 PWO crystals delivered continuously for projects at JLab since 2017
- Crystals used for both NPS and FCAL-2
- All 1100 NPS crystals for NPS passed the NPS quality assurance tests (similar for FCAL-2)

CRYTUR is a well established and tested vendor that can deliver crystals of the quality needed for EIC



EIC crystals are rectangular like NPS crystals with similar tolerances

Length uniformity of CRYTUR crystals (2017 – present)



Average: 199.95 mm +0/-0.02 mm

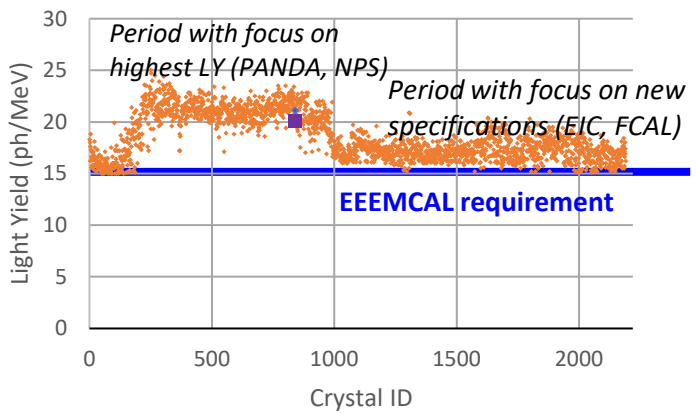
Consistent with EEEMCAL tolerance

$PbWO_4$ Quality Assurance Protocol

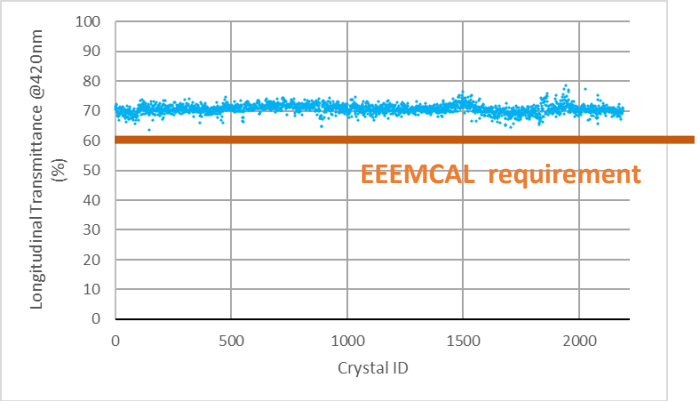
- The quality assurance will build on the process developed for NPS and will consist of:
  - 2 step visual inspection
  - mechanical dimension measurement
  - light yield measurement
  - Kinetics
  - transmittance measurement
  - induced radiation absorption coefficient.
  - (as needed surface/chemical analysis)
- Measurements may be carried out at one or more of the QA facilities
  - cross calibration of the setups and systematic checks

Characterization results of CRYTUR produced crystals (2017 – present)

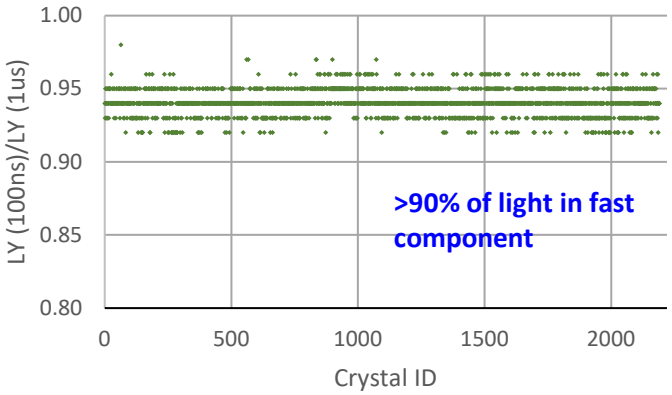
Light Yield (LY)

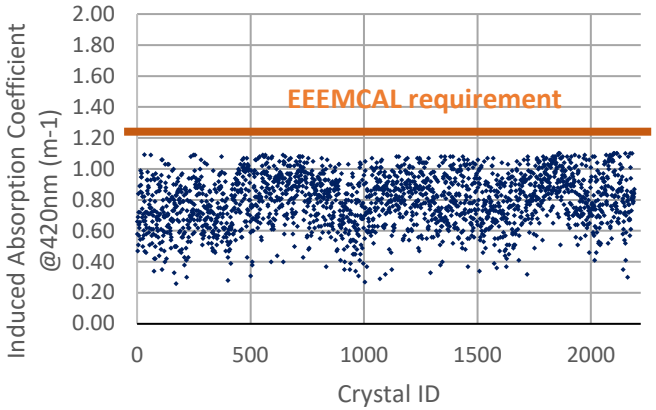


Longitudinal Transmittance



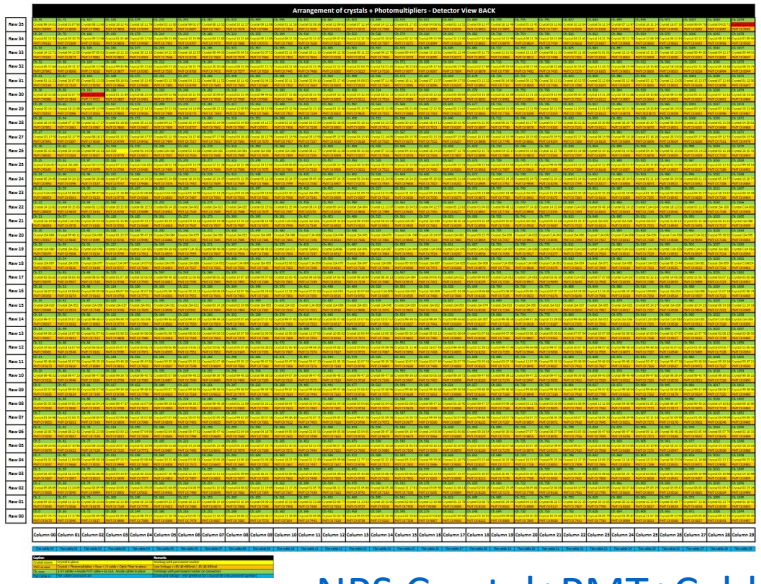
Kinetics





$PbWO_4$ Quality Assurance Documentation

- Crystal quality assurance results will be documented in a central location, e.g., a master spreadsheet or Wiki
  - Crystals will be tracked by ID – also needed for later module assembly



NPS Crystal+PMT+Cable module map

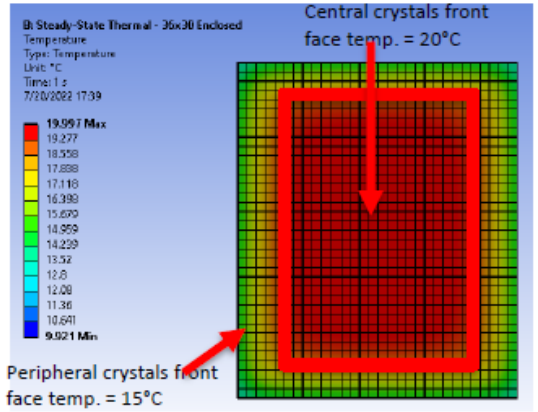
CUA 0000093598 (2019)

ID #	T 360 nm [%]	T 420 nm [%]	T 620 nm [%]	LY [ph/MeV]	LY (100 ns)/LY (1ms) +/- 3%	Dk (420 nm)	L meas.	W1 meas.	W2 meas.	W3 meas.	W4 meas.	W5 meas.	W6 meas.	W7 meas.	W8 meas.
CUA-001	41.7	67.6	77.1	15.3	94	0.84	199.93	20.43	20.45	20.43	20.44	20.45	20.46	20.48	20.48
CUA-002	48.5	68.9	77.2	15.6	95	0.61	199.97	20.46	20.45	20.46	20.45	20.47	20.44	20.47	20.44
CUA-003	41.7	68.6	77.9	15.8	95	0.570	200.00	20.46	20.46	20.46	20.46	20.47	20.47	20.47	20.47
CUA-004	44.2	69.3	78.8	15.1	94	0.610	199.98	20.46	20.46	20.46	20.47	20.44	20.45	20.44	20.45
CUA-005	41.1	68.0	77.9	16.2	94	0.6	199.99	20.45	20.48	20.44	20.46	20.47	20.46	20.46	20.46
CUA-006	42.7	67.5	78.5	17.7	94	0.79	199.91	20.43	20.42	20.45	20.43	20.46	20.42	20.47	20.43
CUA-007	44.5	68.9	78.3	17.0	95	0.63	199.97	20.43	20.42	20.43	20.42	20.46	20.46	20.47	20.47
CUA-008	45.9	69.1	77.7	16.3	94	0.78	199.94	20.44	20.42	20.50	20.47	20.45	20.45	20.44	20.44
CUA-009	48.0	71.5	78.1	15.1	94	0.53	199.95	20.49	20.49	20.48	20.48	20.46	20.48	20.48	20.50
CUA-010	47.5	70.4	78.0	15.7	95	1.01	199.95	20.47	20.47	20.47	20.47	20.48	20.48	20.50	20.50
CUA-011	48.6	71.5	78.4	17.1	93	0.38	199.96	20.48	20.48	20.47	20.47	20.48	20.50	20.47	20.49
CUA-012	45.6	69.6	78.1	16.4	94	0.98	199.96	20.49	20.47	20.49	20.47	20.48	20.48	20.49	20.50
CUA-013	48.4	71.8	78.1	17.2	95	0.74	199.96	20.49	20.47	20.48	20.46	20.49	20.48	20.50	20.49
CUA-014	47.2	71.2	78.0	15.9	93	0.53	199.96	20.47	20.47	20.47	20.47	20.50	20.48	20.50	20.48
CUA-015	47.3	71.0	78.2	16.7	93	0.99	199.96	20.45	20.44	20.44	20.43	20.46	20.47	20.48	20.49
CUA-016	48.4	71.5	78.6	15.1	94	0.62	199.96	20.45	20.46	20.46	20.46	20.45	20.45	20.46	20.46
CUA-017	45.1	70.8	78.9	16.8	94	0.72	199.97	20.46	20.47	20.47	20.47	20.47	20.47	20.50	20.50
CUA-018	40.9	69.6	78.6	16.5	94	0.83	199.97	20.43	20.46	20.44	20.47	20.47	20.49	20.48	20.50
CUA-019	48.1	71.1	78.6	17.9	94	0.62	199.96	20.49	20.48	20.49	20.48	20.48	20.49	20.48	20.48
CUA-020	46.7	69.6	77.5	15.4	94	0.66	199.95	20.46	20.47	20.47	20.48	20.49	20.49	20.49	20.49
CUA-021	46.2	70.0	77.7	15.0	94	0.88	199.96	20.46	20.46	20.47	20.47	20.48	20.47	20.48	20.48
CUA-022	49.0	72.6	78.9	17.2	94	0.65	199.94	20.48	20.46	20.47	20.45	20.48	20.48	20.49	20.49
CUA-023	48.1	71.1	78.3	15.7	94	0.57	199.96	20.48	20.49	20.48	20.48	20.50	20.50	20.50	20.50
CUA-024	46.7	71.1	78.0	15.1	94	0.87	199.96	20.48	20.48	20.48	20.48	20.50	20.48	20.50	20.49
CUA-025	46.5	71.1	78.3	16.5	94	0.74	199.95	20.48	20.47	20.48	20.47	20.47	20.48	20.48	20.49
CUA-026	47.6	71.4	78.2	15.0	94	0.89	199.96	20.49	20.49	20.49	20.49	20.48	20.49	20.48	20.49
CUA-027	46.7	70.9	78.1	15.3	94	0.73	199.96	20.49	20.49	20.48	20.48	20.48	20.47	20.49	20.48
CUA-028	47.9	71.4	78.1	16.2	94	0.66	199.98	20.49	20.48	20.49	20.48	20.50	20.44	20.50	20.45
CUA-029	47.9	70.8	78.4	15.1	95	0.69	200.00	20.48	20.48	20.47	20.47	20.49	20.48	20.50	20.50

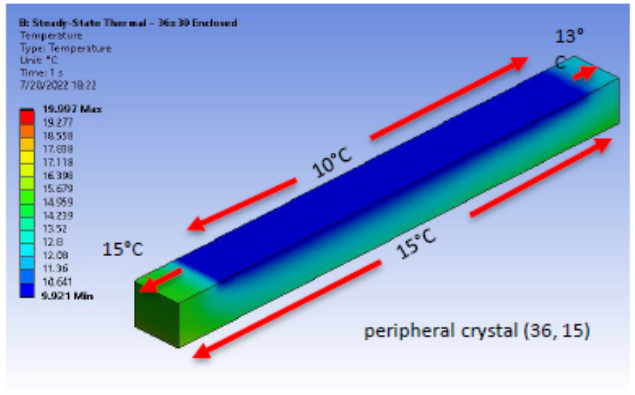
Crystal characterization results

Ansys Thermal Analysis

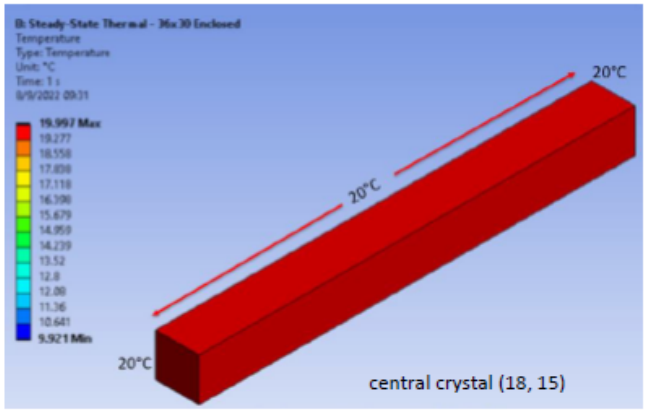
- Heat load of 0.3 W applied to the rear face (PMT end) of each crystal



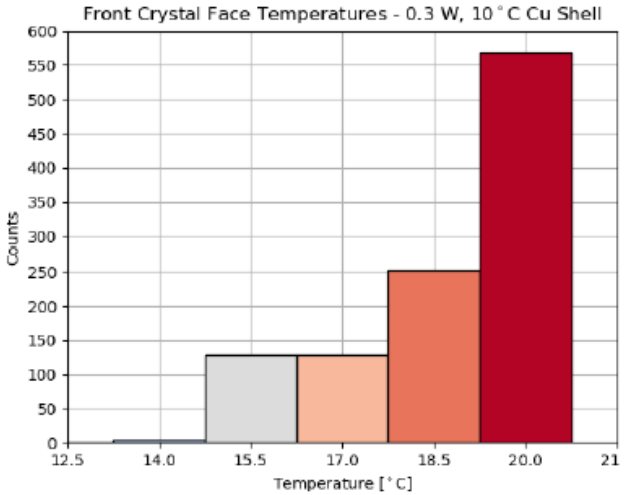
Temperature distribution on front face of crystal



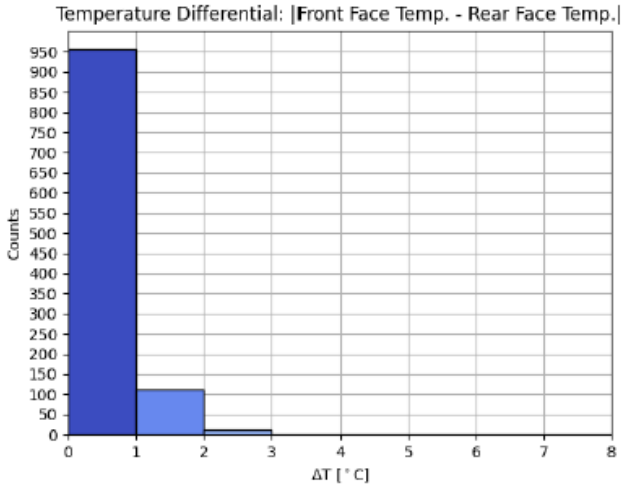
~15°C at front and ~13°C at rear; ΔT=2°C



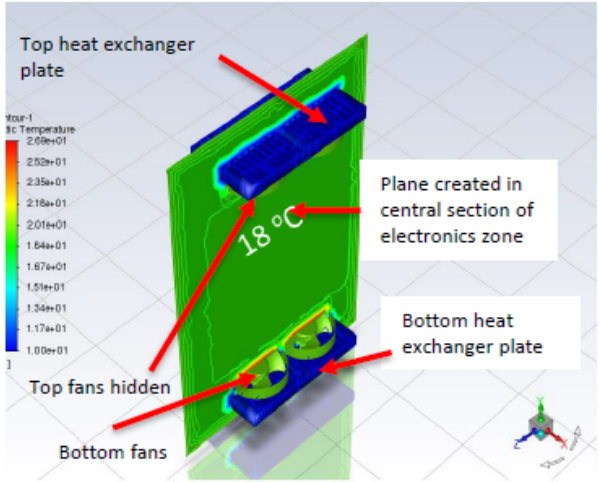
~20°C at front face and ~20°C at rear face; ΔT=0°C



Crystal temperatures; 575 crystals at ambient temp of 20°C



ΔT of crystals; ~128 crystals have ΔT>1°C; light yield might be affected for crystals with ΔT>2°C



Isometric view of electronics zone temperature when four fans blow air at 3.33 m/s to the heat exchanger plates, which are at 10°C