PbWO4 Studies in 2014/2015 and Plan for 2015/2016

Summary of studies in 2014-2015

- ***15 crystals were delivered from SIC in 2014 (#1-10 in spring & #11-15 in December)***
  - The measured dimensions of crystals are 20±0.15 mm × 20±0.15 mm × 200±0.15 mm.
  - Visual inspections show that most of crystals were good quality, but some of them have small scratched on side or front surface.
- ***Optical properties of crystals***
  - At ***JLab*** the longitudinal and transverse transmittances for 15 crystals have been measured. The reproducibility of the measurements is on the order of a few percent, main uncertainty is crystal orientation. For most of crystals transmittance starts around 350 nm and reaches to ~90% at $\lambda > 500$ nm. The longitudinal transmittance (20 cm thickness) varies between 60% and 70% for most crystals at a wavelength 420 nm. One of the crystals (#14) shown a completely different behavior above 480 nm. The transmittance in the transverse direction (2 cm thickness) was measured at several distances ranging between 5 and 55 mm from the face of the crystal. The crystal-to-crystal variation of the transverse transmittance seems to be much less than what was observed for the longitudinal transmission. However, the transmittance of one of the crystals (#9) is significantly lower than that of the other crystals.
  - ***Giessen*** studies show that longitudinal transmittance of blocks #2, 3, 6, 8 and #9 on average are lower by 10-15% than data measured at JLab. While, for transverse transmittance there are only small difference between Giessen and JLab data.
  - ***BNL*** data show that longitudinal transmittance of blocks #7 and #15 are lower than data measured at JLab.
  - ***Caltech*** studies show that sample #11 has significant scattering centers. Sample #5 shows better LT than sample #11 because of less scattering centers.
  - A comparison ***Caltech*** and ***JLab*** data for the crystal (#5) shows that transmittance measured at Caltech with integrating sphere is higher than JLab.
  - It is interesting to note that there seems to be a significant difference in the shape of the distributions between the ***JLab*** and ***Giessen*** in the region around 400 nm.

- **Light yield**
  - At ***Giessen*** the light yield for a subset of 15 crystals (#2, 3, 6, 8 and #9) at room temperature (+18°C) measured and found on the order of 15-16 pe/MeV though some of crystals show a lower yield of only 12 pe/MeV.
  - ***Giessen*** data also show that the light yield increases by a factor of about three due to cooling to -25 °C.
  - At ***CUA*** setup based on radioactive source ^{22}Na (511 keV photons) have been used to study temperature dependence of the light yield. Data show that LY increases with temperature by ~2.4% per 1°C which is consistent with CMS and Giessen data.
  - ***Caltech*** studies show that light output of crystals #5 (15.6 p.e./MeV) and #11 (12.4 p.e./MeV) are better than CMS SIC (11.4 p.e./MeV).

- ***Timing***
  - ***Caltech*** studies show that two crystals (#5 and #11) are faster than CMS PWO crystals. Fraction of Light Output (LO) in 50/100 ns for sample #5 and #11 is 91/99%, while for CMS crystals is 84/96%.
- ***Radiation hardness***
  - At ***JLab*** irradiation using γ-source (single source ^{137}Cs) with a dose rate of ~260 rad/h. No sign of radiation damage was observed up to ~300 krad
  - At ***Idaho*** irradiation with 20 MeV electron beam at dose rate 1.3 Mrad/h show high resistance of the SIC crystals. The transmittance of some of crystals (#2, 4 and #8) changed ~15% after accumulated dose 432 krad (at dose rate of 1.3 Mrad/h), while others (#3, 5 and #6) do not seems show any effects of radiation damage. To minimize spontaneous recovery effect all transmittance measurements were carried out 10 minutes after exposures. For irradiation at dose rate 1.3 Mrad/h for 20 min exposure the temperature near the crystal front increased from ~74°F to ~98°F. For similar exposure time at dose rate 2.6 Mrad/h the temperature increases from 76°F to 115°F resulting in crystal damage.
  - At ***Giessen*** the longitudinal transmittance for subset of crystals (#2, 3, 6, 8 and #9) was determined before and after gamma irradiation (5 radioactive sources ^{60}Co) with an integral dose of 30 Gy within 15 minutes. The impact of radiation effects were quantified in terms of the change in the absorption coefficient *k*, and found to be from $dk{\sim}0.4\ m^{-1}$ (crystal #03) to $\sim 1.3\ m^{-1}$ (crystal #02), which is better than CMS quality requirement ($\sim 1.6\ m^{-1}$).
- ***Curing***
  - IR curing with 4 LEDs (950 nm) at current 75 mA and distance 1 cm for 12 hrs
  - Blue light curing with 4 LEDs (360 nm) at current 50 mA for 3 hrs
  - Curing strategy does not seem to recover the optical quality of the crystal #2 irradiated at ~2 Mrad radiation dose.
  - Thermal annealing for 10 hrs at 200°C (with ramp up-down rate 20°C/h) have been performed for all 15 crystals.
- ***Summary of 2014/2015 studies***
  - **Our studies of a set of fifteen crystals produced by SIC in 2014 seem to indicate that the overall quality mostly conform to CMS/PANDA requirements.**
  - **The optical transmittance seems consistent with CMS quality** and relatively uniform along the crystals. However, there is a global variation from crystal to crystal on the order of 20%.
  - **The light yield of the crystals also seems to be consistent with CMS quality** standards (12-16 p.e./MeV).
  - However, understanding the effect of systematics on the optical measurements is important for the interpretation of crystal quality.
  - Results from Caltech suggest that the measured values of the transmittance are higher than those for JLab measurement.
  - Results from measurements at Giessen and BNL show similar features in that the measured values of the transmittance are lower than those for the JLab measurement.
  - **A quantitative analysis of the homogeneity of the crystals must be done to fully characterize the crystal quality achievable.**

Plan for 2015/2016

Note, 30 more crystals were ordered from SIC in spring 2015

- ***Need full information about Composition of the crystals***
  - Chemical composition of raw materials
  - Details of growing process. (Are all crystals made from the same raw material?)
- ***Check Geometrical accuracy and surface quality of the crystals***
  - Visual inspection, cracks
  - Tolerance in dimensions
  - Surface quality (roughness)
- **Check crystals intrinsic radioactivity**
  - Activity of the crystals and decay products (in a good shielded low background box)
- **Light yield measurements**
  - Photon per 1 MeV
  - Temperature dependence
- **Timing quality**
  - LY(100 ns)/LY(1 μs)
- **Optical Transmission**
  - Study accuracy of the measurements
  - Longitudinal transmission
  - Transverse transmission (at 5-6 positions along the crystal)
- **Radiation hardness**
  - Irradiation with γ-source
  - Irradiation with electron beam
  - Transmission measurements before and after irradiation
- **Spontaneous recovery of radiation damage and curing**
  - Spontaneous recovery of the radiation induced damage (dk)
  - Blue and Infra-red curing
- **Photo-sensors for NPS (selection of option)**
  - Phototube: geometric efficiency, QE, Gain, dark current, rate/timing, price/channel
  - LAAPD: geometric efficiency, QE, Gain, dark current, rate/timing, price/channel
- **NPS prototype tests**
  - Improve/Modify existing 3×3 prototype or build new 5×5 prototype
  - Study energy resolution
  - Calibration and monitoring
  - Temperature-controlled frame

$PbWO_4$ crystal quality specifications for mass production order

Parameter	Unit	NPS	NPS	CMS	PANDA

		Required	Acceptable	Limit	Limit
Light Yield (LY) at RT (for all sides polished crystals)	pe/MeV	≥15	≥10	≥8	≥16
LY uniformity between blocks	%	10%	20%		
LY(100ns)/LY(1μs)	%	>95	>90	>90	>90
Longitudinal Transmission at λ=360 nm at λ=420 nm at λ=620 nm	 % % %			 ≥25 ≥55 ≥65	 ≥35 ≥60 ≥70
Transverse Transmission and LY uniformity along crystal	%	10	15		
Inhomogeneity of Transverse Transmission Δλ at T=50%	nm	≤5	≤10	≤3	≤3
Induced radiation absorption coefficient Δk at λ=420 nm and RT, for integral dose >100 Gy	m^{-1}	<1.0	<1.5	≤1.6	≤1.1
Mean value of dk	m^{-1}	≤0.75	≤1.0	≤1.5	≤0.75
Tolerance in Length Tolerance in sides	μm μm	≤±100 - ≤±50	≤±150 ≤±100	+0., -100 ≤ ±50	±50 ±50
Surface polished, roughness Ra	μm	≤0.02	≤0.05	≤0.02	
Rectangularity (90°)	degree				<0.01
Purity specific. (raw material)				5N–6N	
Mo contamination	ppm	<10		<10	<1
La, Y, Nb, Lu contamination	ppm	?		≤100	≤40