Summary of $PbWO_4$ and Prototype Studies

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Crystal Characterization

Transmittance measurements

- ***Apparatus/method:*** Carl Zorn's setup in the ARC. The device consists of Xenon lamp as a light source, a monochromator, 2 focusing lenses, a table to hold sample, an integrating sphere, and a PMT.
- ***Measurements:***
    - Control measurements to estimate the uncertainty on the transmittance
    - $PbWO_4$ (produced by SIC 2014) measured longitudinally through 20 cm thickness multiple times. The measurements agree with each other within ±1% (absolute).
    - PbF_2 (from Hall A DVCS calorimeter)
    - $PbWO_4$ (produced by SIC 2000 for the CMS) measured through 3 cm thickness at different wave lengths.
- ***Results:***
    - The accuracy of transmittance measurement after optimization of the light beam optics is 0.5-1.5%
    - $PbWO_4$ (>85% is scintillation) and PbF_2 (pure Čerenkov) crystals both have high transparency. The transparency of PbF_2 slowly rises from zero at 250 nm reaching ~70% at wavelength λ~325 nm and its maximum value of ~80% at 450 nm. The transparency of $PbWO_4$ rapidly increases from zero at ~340 nm to 60% at 370 nm, and reaches its maximum value of ~70% above 450 nm.
    - Comparison of data taken with 20 cm and 3 cm thick crystals (both produced by SIC in 2000) suggests no dependence of the transmittance on the thickness. The transmittance of the 3cm (20cm) thick crystals was measured to be 70% (72%) at 420 nm, 74% (74%) at 500 nm and 77% (75%) at 600 nm. These measurements were done before the light beam optics were optimized and the corresponding uncertainty on these measurements is 3-4%. After the optics were optimized measurements for the 20cm thick crystal show a 3-4% improvement on average. No data are available for the 3cm thick crystal after the optics improvement.
    - Comparison of $PbWO_4$ and PbF_2 crystal transparencies show that they are very different in the short wavelength region (λ~250-350 nm), but both reach maxima above λ~450 nm). Hence a common light source with a wave length >500 nm should be acceptable for a Gain Monitoring System of a combined calorimeter with PbF_2 and $PbWO_4$ crystals.

Crystal Irradiation

- ***Irradiation details:*** Several crystals of different sizes (~1.5 cm^3, 3.0×3.0×18cm^3 produced in 2000 by BTCP/SIC for CMS, and 2.0×2.0×20 cm^3 produced in 2014 by

SIC) were irradiated with a dose rate of ~260 rad/h generated by γ-radioactive source ^{137}Cs at JLab). All crystals were exposed from one end (3.0×3.0 cm^2 or 2.0×2.0 cm^2). The total integrated doses varied from 18 krad to 270 krad.

- ***Measurements:***
  - Longitudinal and transverse transmittances of the 18 cm (BTCP, SIC) and 20 cm (SIC) long crystals were measured before and after irradiation.
  - One of the irradiated crystals (18 cm long, BTCP/SIC) was cured by IR light with λ=940 nm (generated by a set of 4 TCAL-7400 LEDs)
  - The 20 cm long SIC crystal was thermally cured at 200 ^{o}C, then irradiated to accumulated dose of 18 krad (with dose rate ~260 rad/hr). At each stage transmittance of the crystals was measured.
- ***Results and discussion:***
  - Only a weak effect on the level of ~2% of possible radiation damage was observed.
  - No definite sign of radiation damage and IR or thermal curing was observed.
  - Very small (practically negligible) radiation degradation of the crystals observed in our studies is not unexpected. The transmittance of $PbWO_4$ crystals from BTCP and SICCAS are measured at CalTech in longitudinal direction, through 22 cm before and after radiation at different rates, after equilibrium in radiation damage is reached. At 400 rad/h rate (relevant to us) the equilibrium is reached at 25 krad integral dose. At 420 nm wavelength (maximum of effect from radiation) the transmittance is decreased by 14% and 11% for BTCP and SIC crystals respectively. Assuming uniform radiation along the crystal, this means 1.5% or 2% effect for 3 cm thickness (marginal for our accuracies).
- ***Conclusion:*** So far, based on our test results we can confirm that $PbWO_4$ crystals at dose rates ~260 rad/h can handle accumulated dose up to ~300 krad without noticeable changes in their optical performance

NPS SUBSYSTEMS AND PROTOTYPING

IR Curing System

a) Choice of IR photodiode

- ***Measurements:*** For two types of infra-red LEDs (LD-274-3 and TSAL7400) the emitted light intensity versus driving current were measured. The Infrared LED was mounted on a special support structure and viewed by a calibrated Photodiode S2281 with an effective area of 100 mm^2 and quantum efficiency of ~67% (at λ~950 nm).
- ***Results and discussion:***
  - The intensity of emitted light is almost linearly proportional to the LED driving current. Beyond 60 mA the output curves slightly indicating the onset of saturation, which is not related to Photodiode. This was checked with measurements with and without attenuator (filter), which gave same result.

  - At a distance of ~3 cm from the photodiode (where the LED fully illuminates the photodiode) and driving current 100 mA the number of emitted photons is ~2 x 10^{16}

γ/s/cm^2. Such flux of photons will deposit power of energy $P_\gamma = N_\gamma \times E_\gamma = 2 \times 10^{16} \times 1.31$ eV/sec $\approx$ **4.2 mW/cm²** (at mean $\lambda \approx 950$ nm).

- ***Conclusion:*** Based on the PANDA group's studies (R. Novotny et al.) the two IR LEDs LD-274-3 and TSAL7400 provide a suitable intensity for IR curing applications.

b) PMT sensitivity to IR light

- ***Measurements:***
  - The R4125 phototube sensitivity to infrared light was studied. The phototube was installed directly in front of the infrared LEDs (LD-274-3 and TSAL7400). The driving current of LEDs was varied from 0 to 100 mA, the PMT high voltage was set for the gain of ~3.8×10^7 (including factor 10 from active divider).
  - It was checked that any IR sensitivity of the PMT is not due to contamination of short wavelength light. For the infrared LED LD-274-3 at distance of 3 cm from the Phototube, and at driving current values 0, 10, 20, 30, 40 and 50 mA the PMT signal spectra was measured with and without 900 nm long-pass filter. (This filter cuts out light below 900 nm).
  - To quantify by how much one shortens the PMT lifetime with IR curing PMT anode current versus LED driving current was measured. The anode current at a typical PMT operating high voltage of 1600 V was about 760 nA.
  - After assembling the prototype with the Gain-Monitoring-System (GMS) the effect of IR light on the PMTs was studied in this configuration. Note, at present infrared LEDs are only mounted in front of three blocks (#2, 5 and 8). For each block there are 4 LEDs and they are connected in series. The total driving current I_o from the power supply is split equally, giving (I_o/3) for each group. To quantify the effect of IR light on the PMT, the prototype PMTs pedestal (width and value), and signal (generated by cosmic particle and GMS) amplitude sensitivity to the IR light intensity (driving current) were studied.

- ***Results and discussion:***
  - These direct tests show that the PMT R4125 has very low but not negligible efficiency to infrared light.
  - There is no difference between measurements taken with and without a 900 nm long-pass filter

- The R4125 maximum anode current given by manufacturer is ~0.1mA. With an anode current of about 0.07mA the IR LED should thus not be dangerous for the PMT, i.e., not shorten its lifetime when using IR curing.
- Data taken with the NPS prototype show that the PMTs (R4125) are sensitive to IR light based on increase of the signal pedestals width. There have not been any observations yet of changes in the PMTs amplitude or resolution due to IR light.
- Data taken with the NPS prototype show a sharp increase in PMTs noise when the IR system runs at a driving current ~150 mA (or about 50 mA for each IR diode) when looking at the PMTs signals on the oscilloscope. The level of noise-signals at PMT high voltage of 1400 V were on the level of ~8-10 mV. The noise was gone when the IR system current was turned down to zero.

- ***Conclusion:*** Future studies are needed to understand how the observations of PMT sensitivity to IR light may impact its long-term stability and live-time. For now, we can only confirm a sharp change in PMTs noise and increase in the pedestals widths when the PMT is exposed to IR light. There does not seem to be an effect on the PMT amplitude and resolution.

NPS Prototype

- ***Design:*** A NPS prototype based on 9 modules from SICCAS has been assembled and preliminary tested with pulser and cosmic rays. The crystals are optically isolated, the PMTs and crystals are in dry contact. The prototype is equipped with a Monitoring System and IR curing system. The Prototype was optimized to eliminate light leaks from the blocks. For the initial tests of curing system, three sets of 4 infrared LEDs were mounted in front of three crystals (4 LEDs for each).
- ***Measurements:***
  - The Gain Monitoring System (GMS) was tested by taking long runs. The input light was from a blue LED driven at frequency 0.8 Hz.
  - The GMS system operated at low intensities was used to calibrate the prototype PMTs by localization of Single Electron Peaks (SEP). The prototype was tested with cosmic rays. Two small 5x10 cm^2 scintillator paddles sandwiched the detector and served as trigger counters.
- ***Results and discussion:***
  - The GMS can run in parallel with data taking in wide ranges of rate and intensity.
  - For the GMS at high voltages of 1.4 kV a cleaner separation of SEPs from pedestals has been achieved.
  - The amplitudes of PMT signals from cosmic rays passing at a distance of ~12.5 cm from the PMTs were typically 40-50 photoelectrons, the summed signal was ~150 p.e.. Given lead tungstate thickness of 6 cm, density 8.3 g/cm^3, energy loss of 1.6

MeV/(g/cm^2) for ~4 GeV muons, this implies ~1.9 photoelectrons per MeV of deposited energy. (Note, with no optical contact between blocks and PMTs).

<u>NPS Upcoming Activities</u>

Testing under experimental conditions at JLab in Hall A

- The prototype will be placed in Hall A and tested during DVCS runs.
- An acceptable location is about 8-10 m distance from the target at ~8 degrees relative to beam-line. This is about middle angle between PbF_2 calorimeter and beam-pipe, and possibly close distance from the target, without disturbing the experiment.
- The expected radiation dose rates at this position for 15 cm LH2 target at 25 uA current was estimated using two methods. In the first the radiation dose rates from NPS proposal were scaled (what was done for Hall C). In the second method the latest simulation data for the Hall A DVCS experiment from Pavel Degtiarenko were used. Both estimations agree within 50% and show that we may expect dose rates ~2 krad/h.
- If all goes well, during DVCS run we will follow crystals degradation by looking amplitude distributions of the signals generated by GMS. To monitor possible variation of the GMS light intensity one of its output fiber will be viewed by reference PMT.

Crystal Irradiation studies with higher dose rates

- We have ordered 5 new crystals from SICCAS, delivery expected before Christmas.
- The plan is to measure the crystal transmittance, perform 200 ^{o}C thermal curing and measure the transmittance again. Before/after that the crystals will be irradiated at dose rates > 5-10 krad at a suitable facility. The effect of degradation and IR curing due to these higher dose rates will be studied.