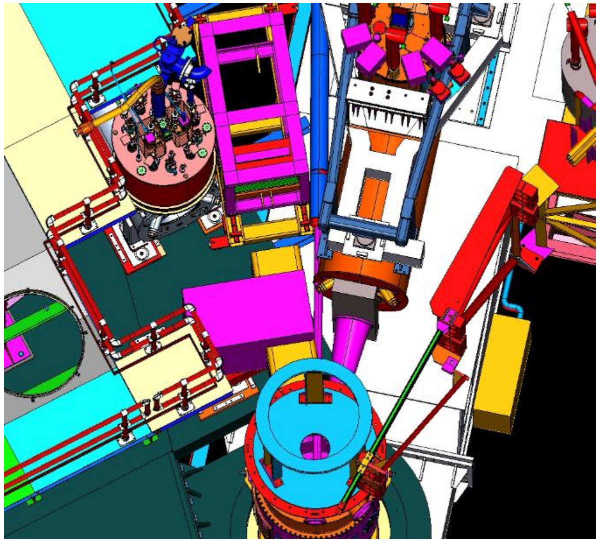
PbWO4 Crystal Performance and NPS Calorimeter Prototype Studies



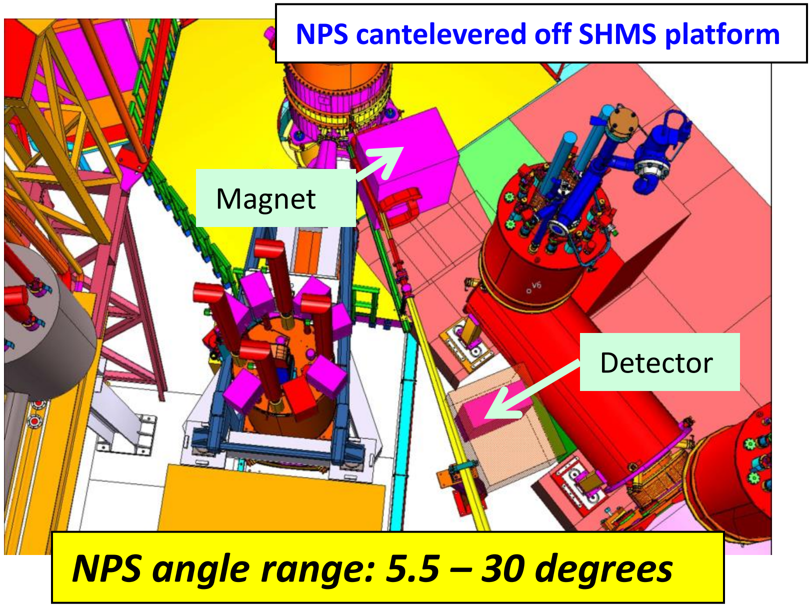
A. Mkrtchyan

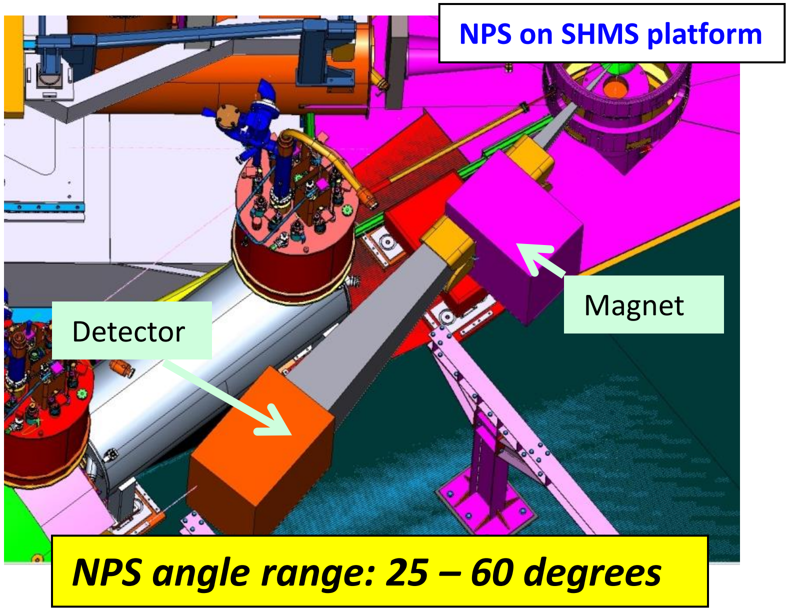
THE CATHOLIC UNIVERSITY of AMERICA

NPS Collaboration Meeting, Jlab, 19 November, 2014

The Neutral-Particle Spectrometer (NPS)

The NPS is envisioned as a facility in Hall C, utilizing the well-understood HMS and the infrastructure of the new SHMS, to allow for precision (coincidence) cross section measurements of neutral particles (γ,π^0).

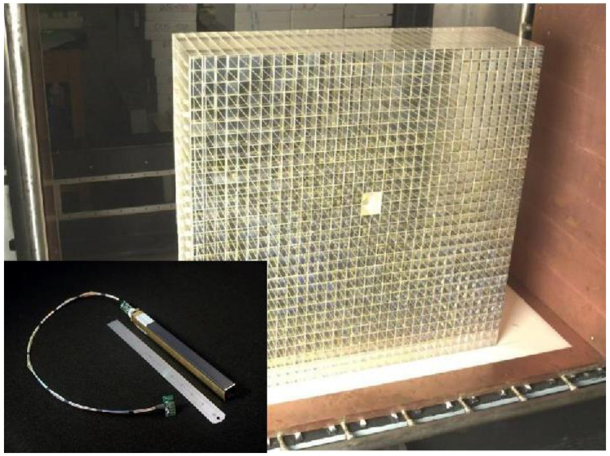


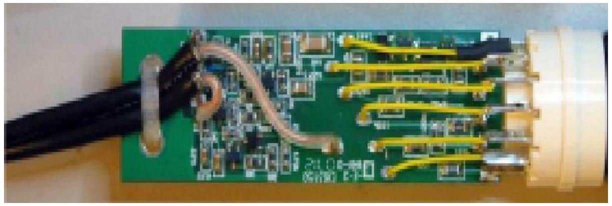


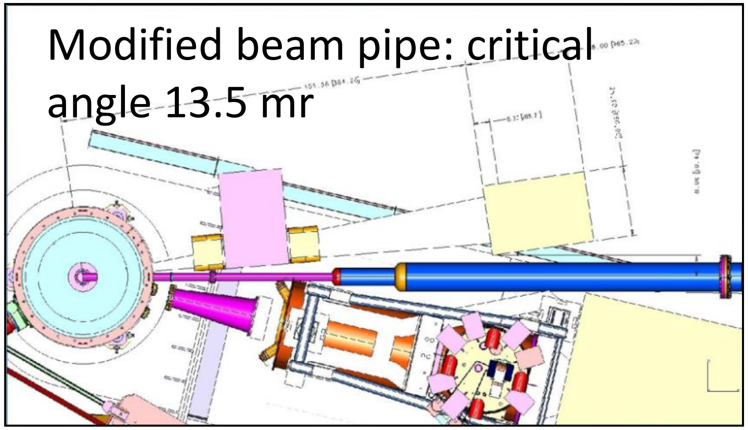
- Currently 5 experiments are ***approved*** by the JLab PAC (three with A-rating), which require the availability of the NPS *→See talk by C. Hyde*
- Ideas exist for new scientific directions, e.g., using a polarized (transverse) target and LD2 *→See talks by J. Zhang, J. Wagner*
- The NPS design is flexible and could also be used in Hall A *→See talk by S. Abrahamyan*

NPS Components

- a ~25 msr neutral particle detector consisting of 1116 $PbWO_4$ crystals in a temperature-controlled frame – using PRIMEx crystals or more likely new.
- HV distribution bases with built-in amplifiers for operation in a high-rate environment – new
- Essentially deadtime-less digitizing electronics to independently sample the entire pulse form for each crystal – JLab-developed Flash ADCs
- Two new sweeping magnets, one horizontal bending with ~0.3 Tm field strength, and one vertical bending with ~0.6 Tm field strength for larger angles/WACS. Both designed to use an existing power supply *→See talk by P. Brindza*
- A Cantelevered platforms off the SHMS carriage to allow for remote rotation (in the small angle range), and platforms to be on the SHMS carriage (in the large angle range) – new
- A beam pipe with as large critical angle as possible to reduce beamline-associated backgrounds – further study showed only a small section needs modification (JLab/Hall C)





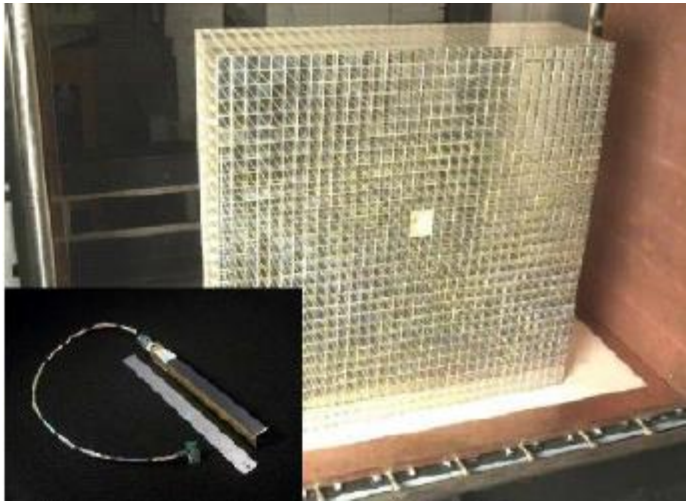


NPS Requirements on PWO

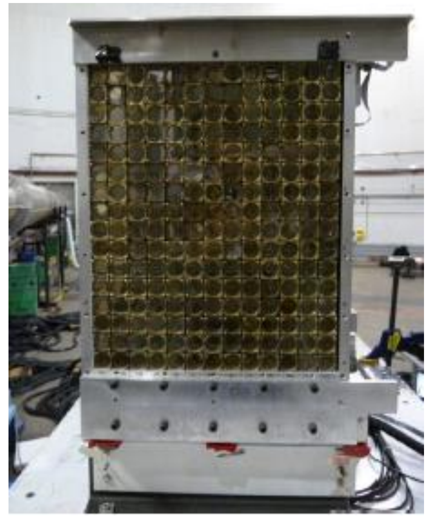
Parameter	Ideal	Acceptable
Light yield (pe/MeV)	10-15	5-6
Transmission (20cm) (%) at λ~420 nm	>60%	~40
Uniformity of optical properties (%)	~10	<20
Radiation hardness LY loss(%) for 1.5 Krad at dose rate 15rad/h	5	~10
Uniformity rad. Degradation at the same dose (20%)	~20	<30
Tolerance in dimensions (um)	+/- 50	+/- 100
Timing property (ns, %)	30-50, 90%	

- ❑ Most stringent requirements are on the light yield (ideally >10 photons/1 MeV) and radiation hardness
- ❑ Also important is timing (~90% emitted light within 30-50 ns)
- ❑ Crystal geometry and integrity: 90 degree angle, 2x2x20 cm^3, roughness <+/- 0.05 mkm, no cracks deeper than 0.5mm

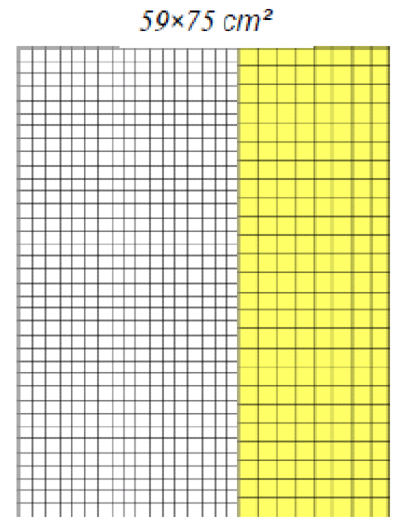
NPS Crystal Matrix



High resolution $PbWO_4$ part from HyCAL

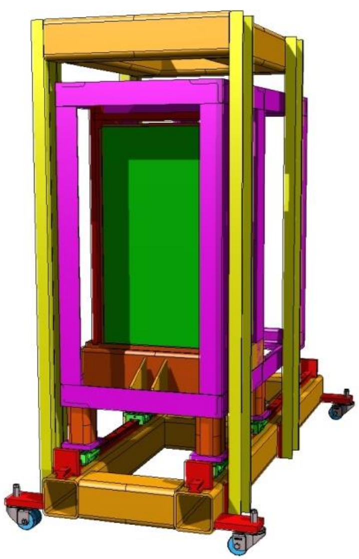


DVCS/Hall A PbF_2 calorimeter



612 $PbWO_4$ + 200 PbF_2

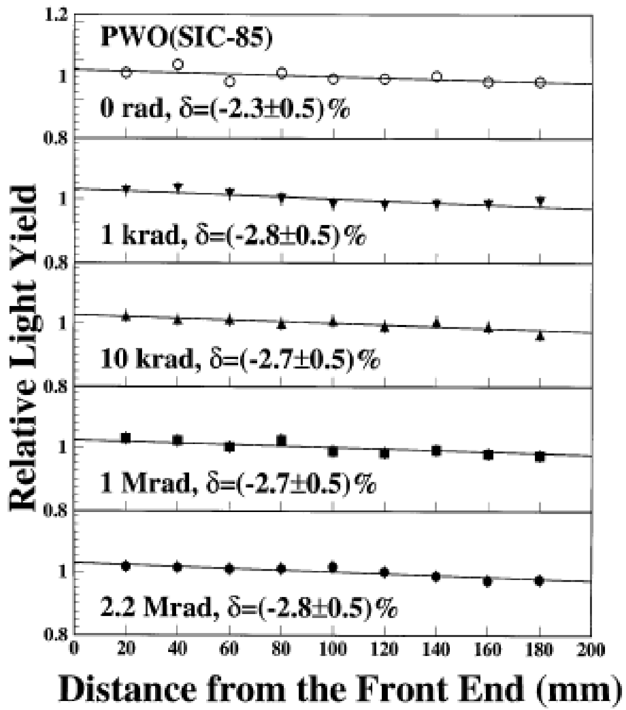
NPS hybrid crystal matrix



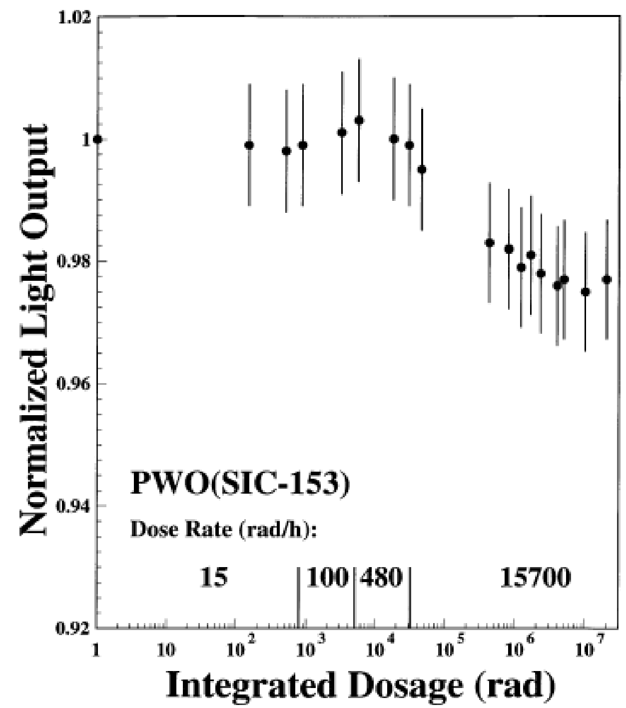
Crystal matrix in NPS frame

- In ideal conditions would start with brand new $PbWO_4$
- Taking advantage of existing $PbWO_4$ crystals from HyCAL, one arrangement is in a 36x30 matrix covering 25 msr at distance of 4 m from target (~1100 crystals)
- Could use PbF_2 crystals from DVCS/Hall A to fill out solid angle if only ~600 $PbWO_4$ available

Effect of accumulated radiation dose for $PbWO_4$



Light response uniformity as a function of the integrated dose

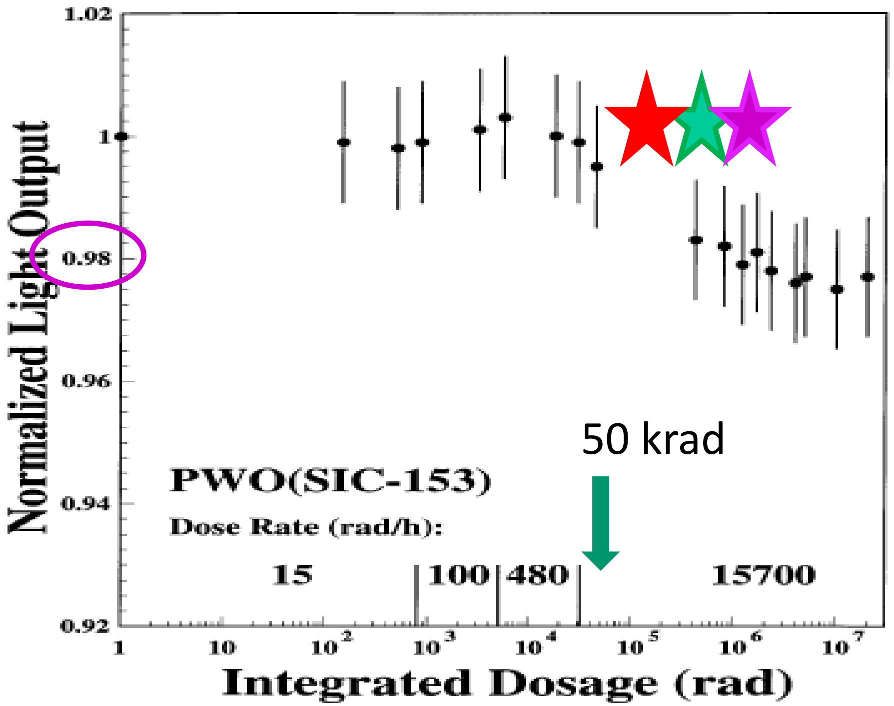


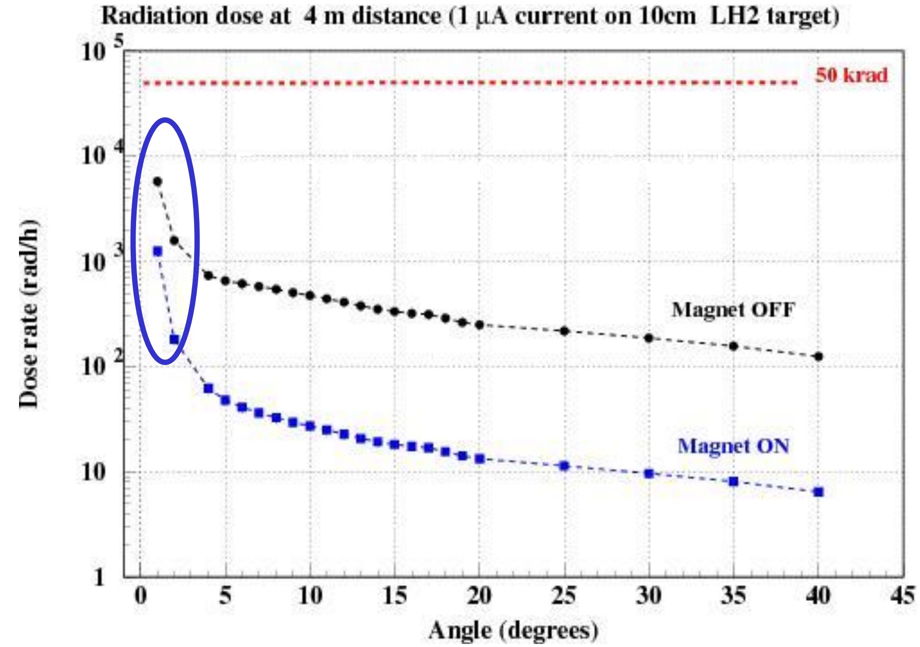
Normalized light output of $PbWO_4$ as a function of integrated dose

[R.Y. Zhu, NIM A 413, p. 297, 1998]

- Light output and slope do not change up to an accumulated dose of 50 krad
    - Small effects up to accumulated doses of ~2.2 Mrad
- Scintillation mechanism is not damaged with only front few cm subjected to radiation dose (dose rates 100-150 rad/h)

Level of Radiation Damage





- LHC radiation dose studies: conservative limit: ~50 krad

  If energy resolution is not a big issue doses of a few Mrad are also ok

- Background simulations show that dose dominated by *small-angle operations*

  [P. Degtiarenko 2012+]

  - E12-13-007: integrated dose < 500 krad
  - E12-14-003: integrated dose = 500 krad
  - E12-13-010 (DVCS): integrated dose = 1.7 (3.4) Mrad in center (edge)

Radiation Damage and Curing

- $PbWO_4$ spontaneously recovers from ~ 1 Mrad damage in ~30 days at ambient conditions.

- Curing strategies for the NPS:

  A) Standard: curing at 400-600 nm wavelengths (optical bleaching)

  - **Requires hall access**, removing front panel and installing the curing system
  - **2 shifts needed** (recovery time ~10-15 hours)
    - may be done opportunistically during accelerator configuration changes or (extended) beam studies

  B) Stimulated recovery with visible and IR light

  - In development stage: *[J. of Phys.: Conf. Ser. 404 (2012) 012063].*
  - Proven to work for shallow doses (~30 Gy)
  - **Can be operated remotely, no hall access needed**
  - Light intensity ~10^{16} photon/s per block, can be supplied by a set of LEDs
  - Fast curing with blue light, with PMTs off
  - Continuous curing with IR, with PMTs on

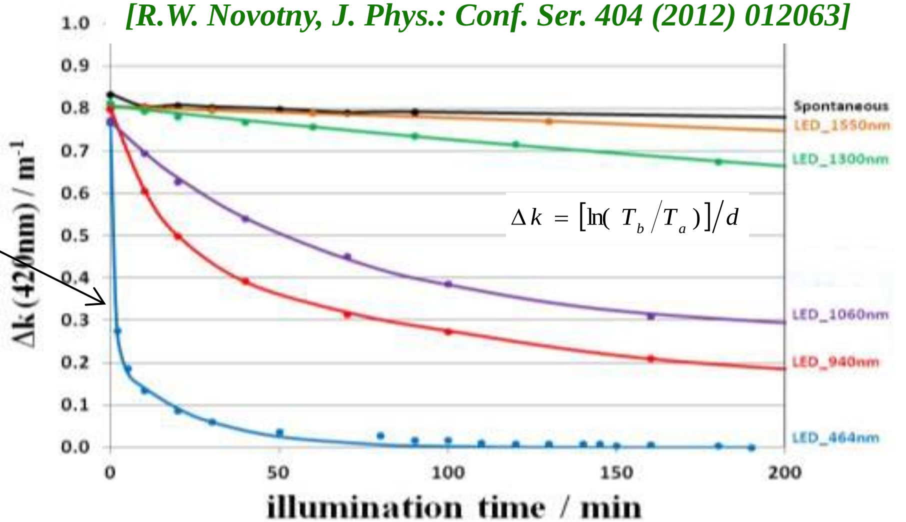
NPS Curing System: optical bleaching

Effective way of $PbWO_4$ *in-situ* curing is <u>optical bleaching</u>.

A) <u>Standard curing</u> at light λ~400-600 nm

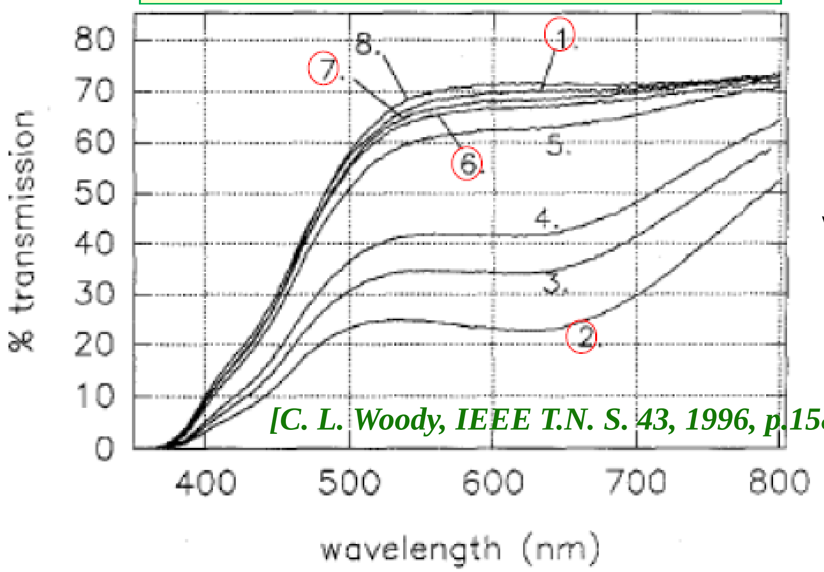
- Curing strongly depends on the wave length, and so fast curing can be done with blue light
- With blue light nearly 90% of the original signal can be restored within first 200 minutes with photon flux of $\sim 10^{16}\ \gamma/s$

[R.W. Novotny, J. Phys.: Conf. Ser. 404 (2012) 012063]



Recovery of 3 krad radiation induced absorption coefficient Δk at 420 nm in a $PbWO_4$, by illumination with different lights.

Transmission of 21cm $PbWO_4$ crystal



[C. L. Woody, IEEE T.N. S. 43, 1996, p.1585]

(1)- before radiation,

(2)- after a dose of 834 krad,

(3)- after 5 h of bleaching at 700 nm,

(4)- after 12 h at 700 nm,

(5)- after 5 h at 600 nm (5),

(6)- after 10 h at 600 nm,

(7)- after 7 h at 640 nm,

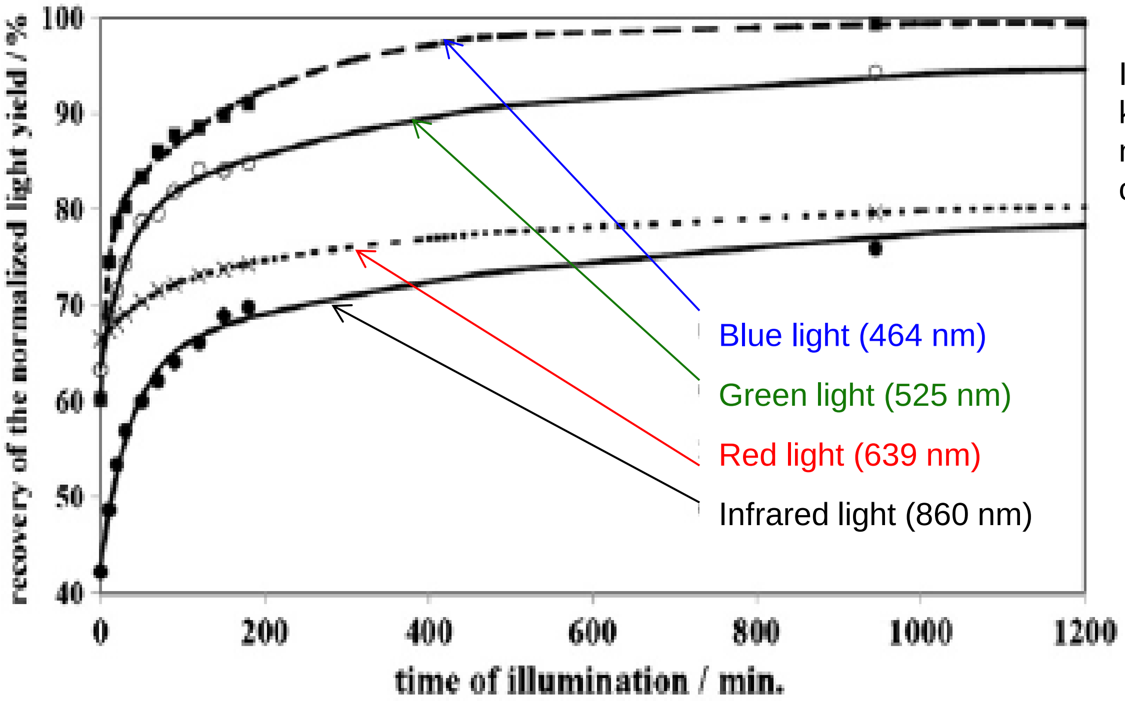
(8)- after 2 h of annealing (200 °C).

NPS Curing System: IR Light

B) Recovery with IR light λ~800-1000 nm

- Works very well for low doses (~3 krad)
- Can be operated remotely, no hall access

[V. Dormenev et al., NIM A623, 2010, p1082]



IR stimulated recovery of 3 krad radiation induced normalized LO of $PbWO_4$ crystal .

- IR curing can be performed continuously, even with PMTs on
- Need light intensity *~10^{16} -10^{17} photon/s* per block, (can be supplied by LEDs)

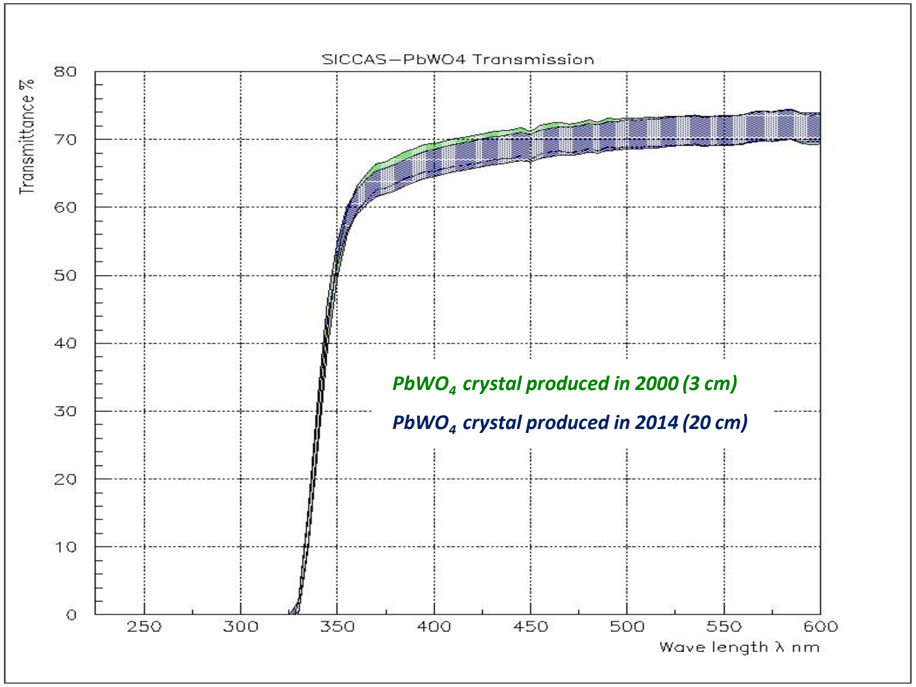
Crystal Characterization: Transmittance

- Several $PbWO_4$ crystals of different sizes produced by SICCAS in 2000 and 2014 were measured
- Data suggest no dependence of the transmittance on the crystal thickness

Crystal thickness	T(%)@420 nm	T(%)@500 nm	T(%)@600nm
3 cm	70	74	77
20 cm	72	74	75

The uncertainty on these measurements is 3-4%.

- Data suggest that the transmittance of crystals produced in 2014 is similar to that of those produced in 2000 within the uncertainty of the measurement



Light Transmission efficiency of the SICCAS $PbWO_4$ (2.0×2.0×20.0 cm3) versus the wave length. Colored area represents the spread between the data measured at different points of the crystals.

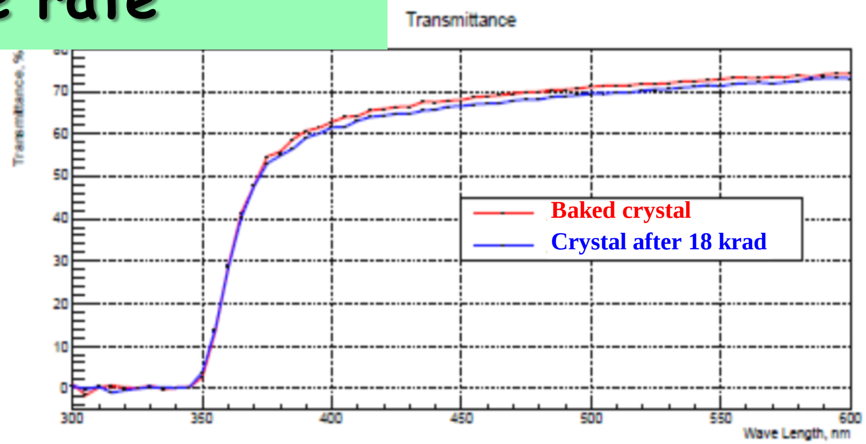
Crystal Characterization: dependence of radiation damage on dose rate

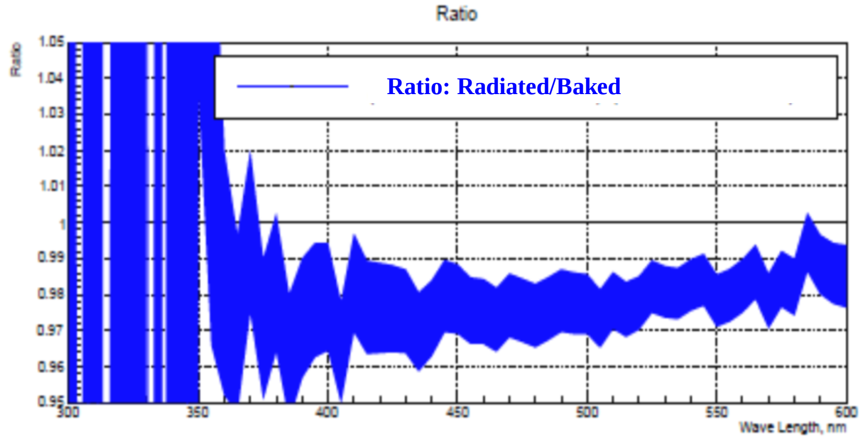
- A 2x2x20 cm crystal (produced in 2014 by SIC) was irradiated by γ-source from one end (longitudinally), at a *dose rate of 260 rad/h (max. available at JLab)*

➢ No sign of radiation damage was observed up to ~300 krad

- The same crystal was baked for 10 hrs at 200°C (with ramp up-down rate 20°C /h), then radiated for 18 krad from one end.

➢ Comparison before and after the radiation shows a ~3% reduction in the transmittance at 420 nm – largely within uncertainty





- Strong γ-radiation damage for the same type SIC crystals were observed at *dose rates of ~20 **k**rad/h [R. Novotny et al., PANDA Int. Rep. 03.07.2014].*

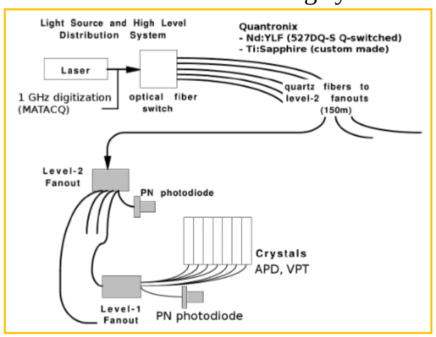
PbWO4 crystals from SIC can handle radiation up to ~300krad at *dose rate 260 rad/h* without noticeable changes in their optical performance

Effects of radiation damage depend strongly on the dose rate – next step

NPS Light Monitoring System

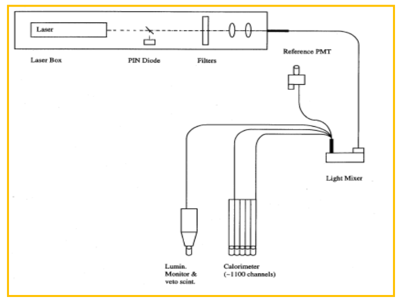
- NPS light monitoring system will provide for calibration and quality control of the crystals and PMTs during long and high luminosity experiments

The CMS laser base monitoring system.

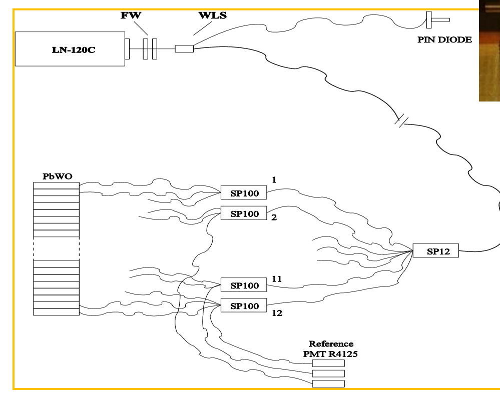


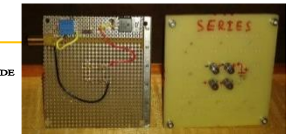
[F. Ferri, J. Phys. Conf. Ser. 404 (2012) 012041]

PrimEx laser base gain monitoring system

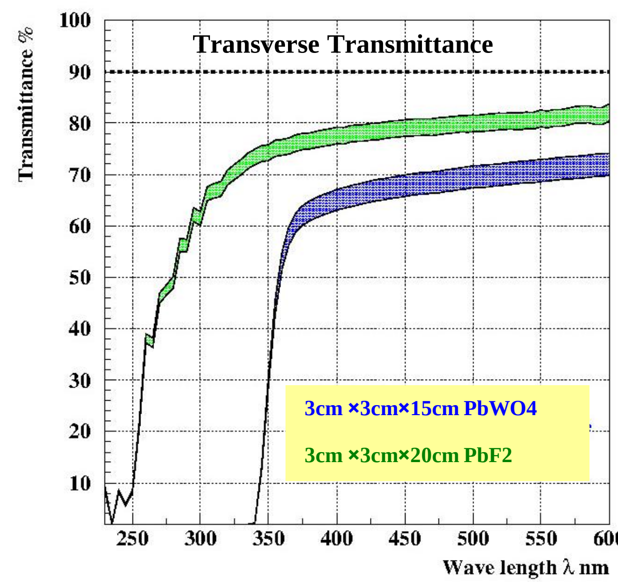


(Adopted from PrimEx CDR)).



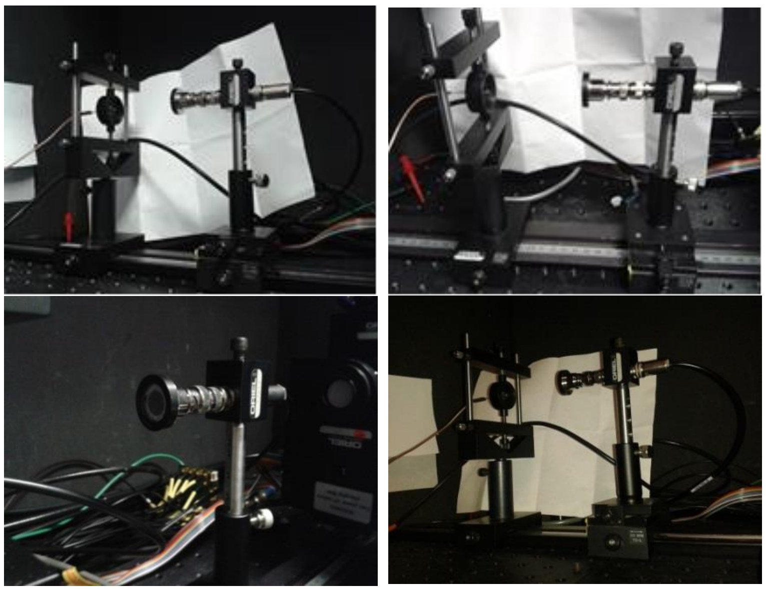


- Light Monitoring System measures the variation of transmittance in crystals and provides calibration in situ
  - Helps monitor condition and to define when curing is needed
  - Design based on that used for Hall C calorimeters and systems developed for CMS, ATLAS, PrimEx, etc.
- Transmittance studies of $PbWO_4$ and PbF_2 show saturation above ~400nm

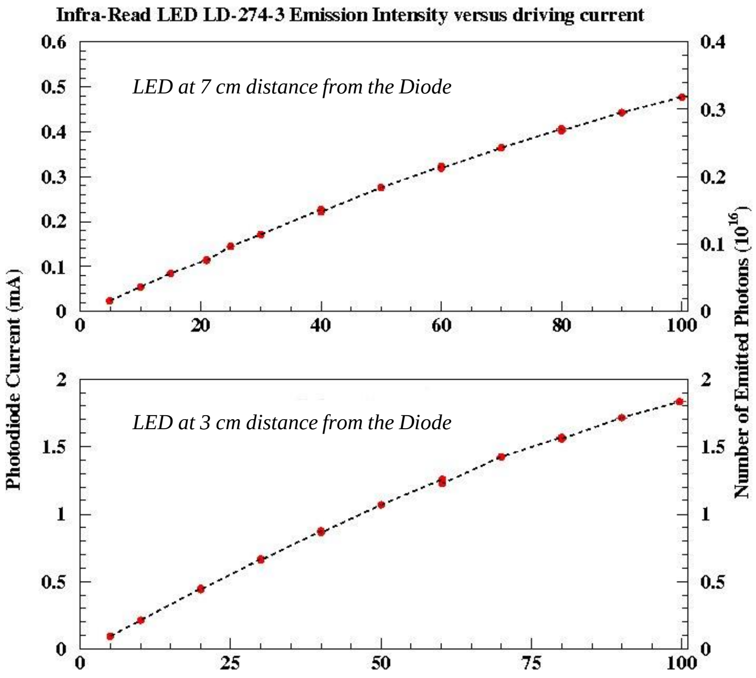


NPS Curing System: Choice of IR photodiode

For two infrared LEDs candidates (LD-274-3 and TSAL7400) the emitted light intensity versus driving current were measured.



The Infrared LED was viewed by a calibrated Photodiode S2281 with an effective area of 1.0 cm^2 and quantum efficiency of ~67% (at λ~950 nm).



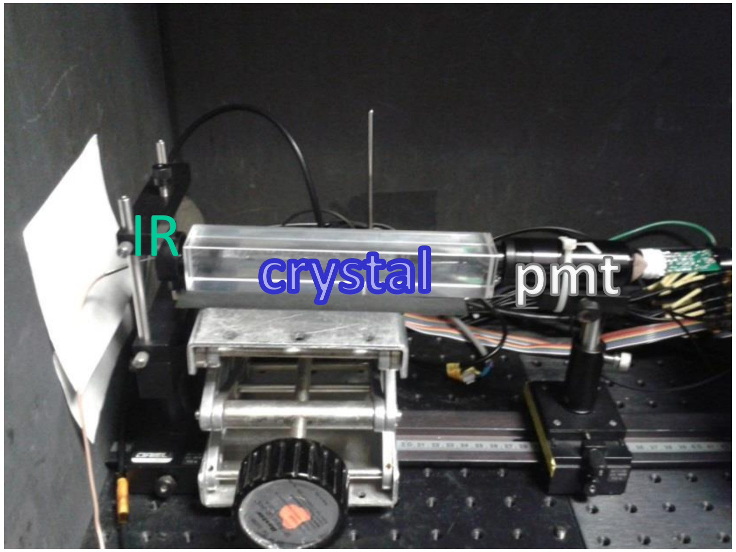
LEDs driving current (mA).

- Intensity of emitted light is almost linearly proportional to the LED driving current.
- At a distance of ~3 cm from the photodiode (where the LED fully illuminates the diode) and driving current 100 mA the number of emitted photons is ***~2×10^{16} γ/s/cm^2*.**

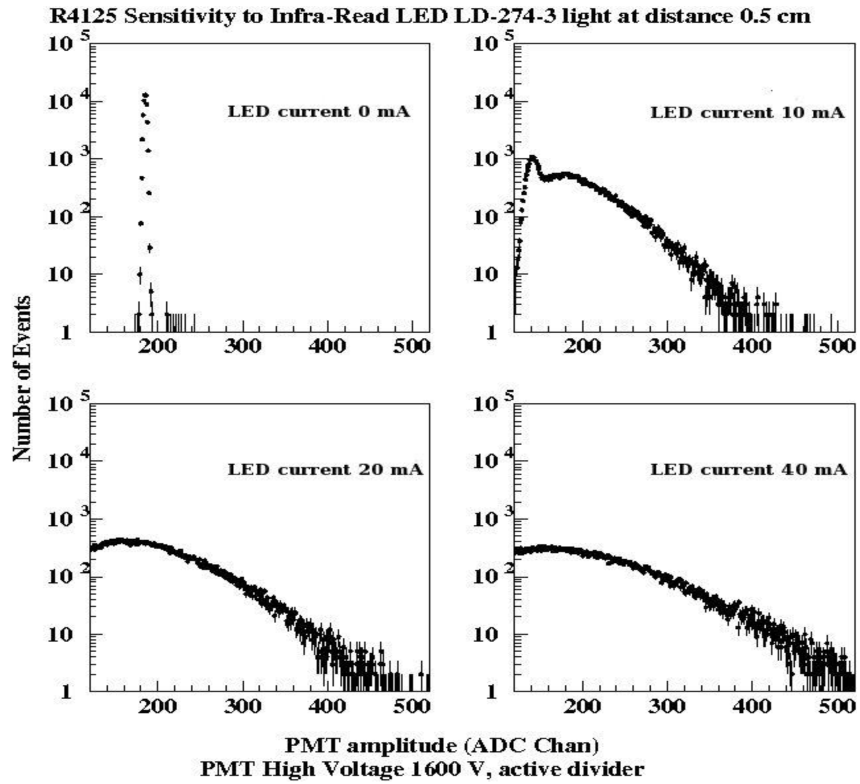
Power of deposited energy $P_\gamma \approx 4.2$ mW/cm^2

Both IR LEDs LD-274-3 and TSAL7400 provide a suitable intensity for IR curing applications

NPS Curing System: PMT sensitivity to IR light



R4125 sensitivity to LD-274-3 and TSAL7400



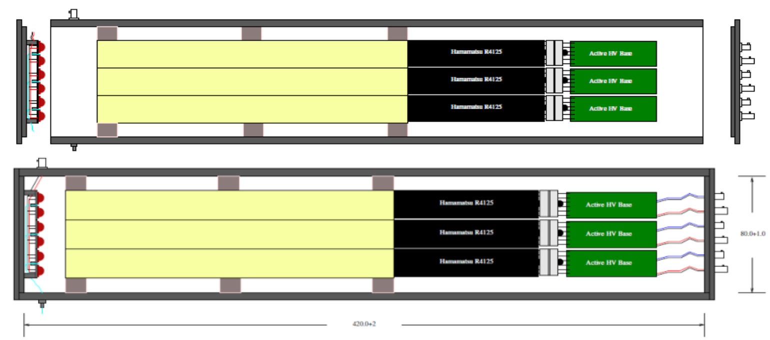
The amplitude distribution of the PMT's noise (dark-current) versus the driving current of the IR diode.

- To quantify by how much one shortens the PMT lifetime by exposure to IR light (~950 nm) the PMT anode current was measured versus LED driving current
  - ➢ The anode current at a typical PMT operating HV of 1600 V was ~760 nA (the R4125 maximum anode current given by manufacturer is ~0.1 mA)
  - ➢ No difference in measurements with and without a 900 nm long pass filter were found

Comparison of the observed anode current of ~0.07 mA and the manufacturer specs suggest that the IR light of LD-274-3 and TSAL7400 should not be dangerous to the R4125

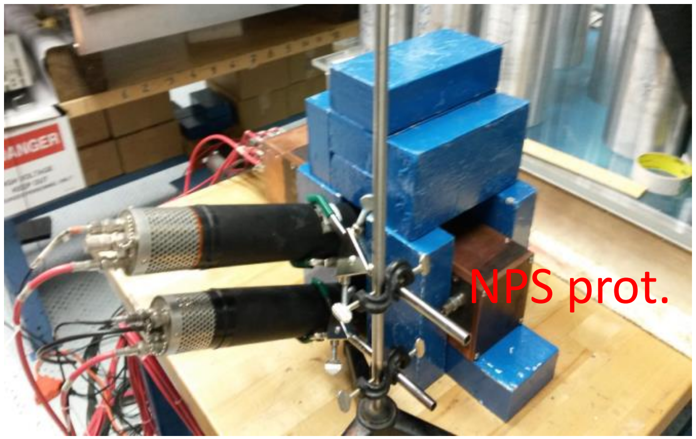
NPS Prototype Design

- NPS prototype is being constructed to optimize technical aspects of the calorimeter before finalizing the design of the NPS



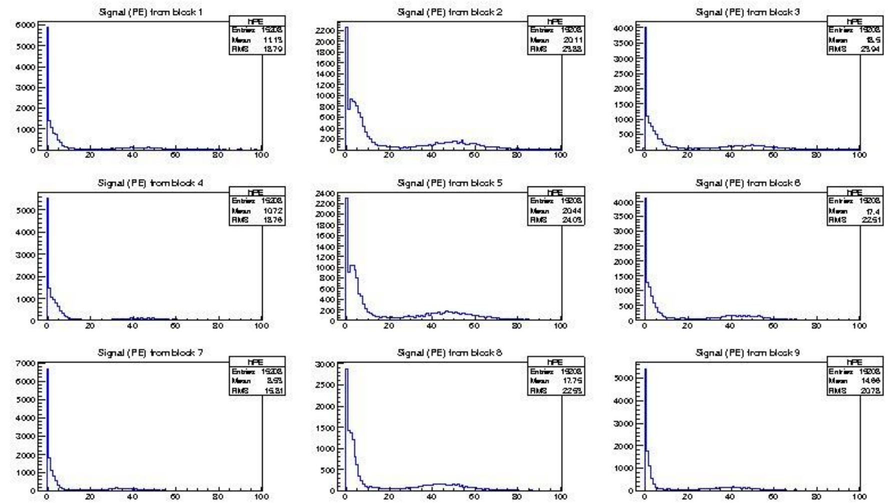
- Components of the NPS prototype
  - Crystal matrix: 3×3 $PbWO_4$ (SICCAS, 2014), each 2.×2.×20. cm^3 in a copper frame
  - Light Monitoring System based on Blue Light source >450 nm (matrix of LEDs)
  - Curing of the crystals will test two approaches:
    - ✓ standard, based on a blue light source (λ~460 nm)
    - ✓ new and currently at development stage, IR curing (λ>900 nm)

NPS Prototype Performance: photon yield

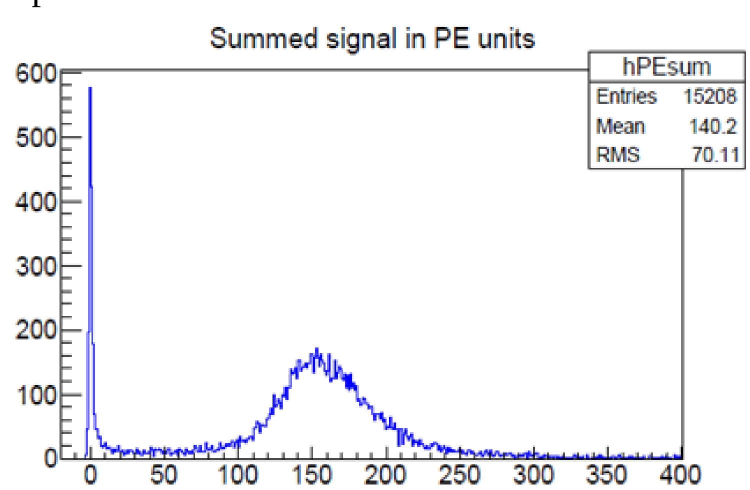


Two small 5x10 cm^2 scintillator paddles sandwich the detector and serve as trigger counters.

The ADC spectrum from cosmic for all blocks



The amplitude of the PMT signals from cosmic rays passing at ~12.5 cm from PMTs is typically 40-50 photoelectrons.

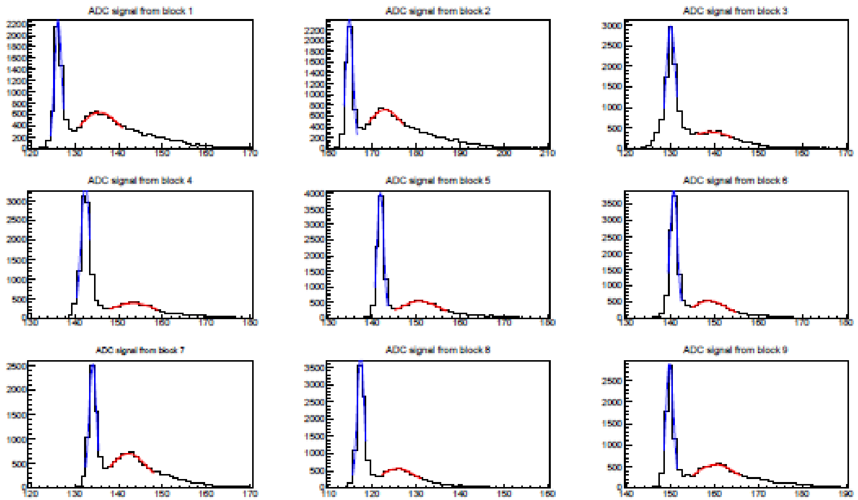


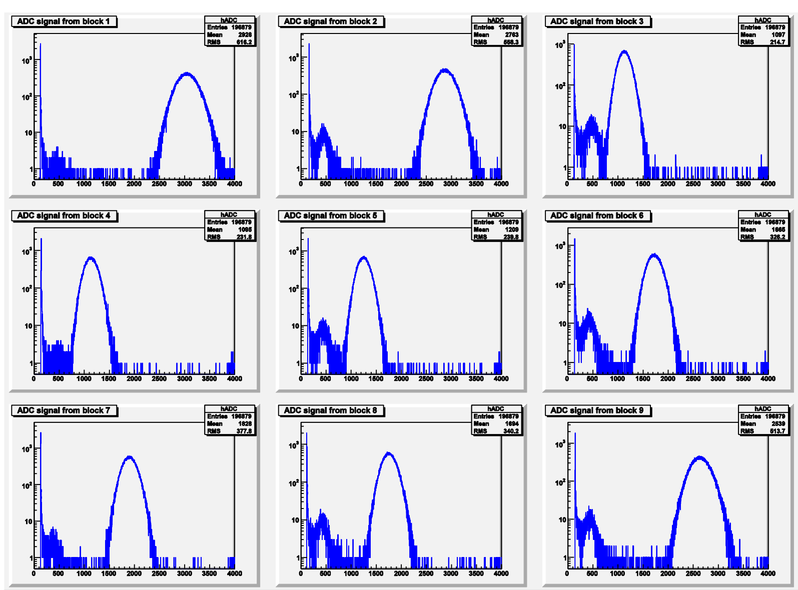
The summed signal is ~150 p.e. Given PbWO thickness of 6 cm, density 8.3 g/cm^3, energy loss of 1.6 MeV/(g/cm^2) for ~4 GeV muons, this implies ~1.9 photoelectrons per MeV of deposited energy. (Note, with no optical contact between blocks and PMTs).

NPS Prototype: performance of the light monitoring system

GMS=Gain (Light) Monitoring System

Single photo-electron distributions used for the PMTs calibration

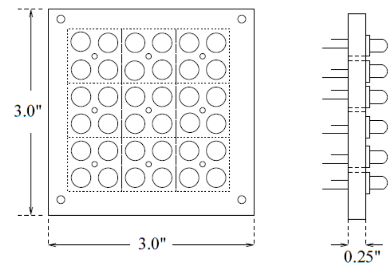




Events at higher channels are generated by GMS, signals from cosmic are located between pedestals and GMS signals.

- Prototype has been tested with cosmic rays and with GMS running at 1 Hz rate.
- At low intensity the GMS system was used to calibrate detector PMTs gain.

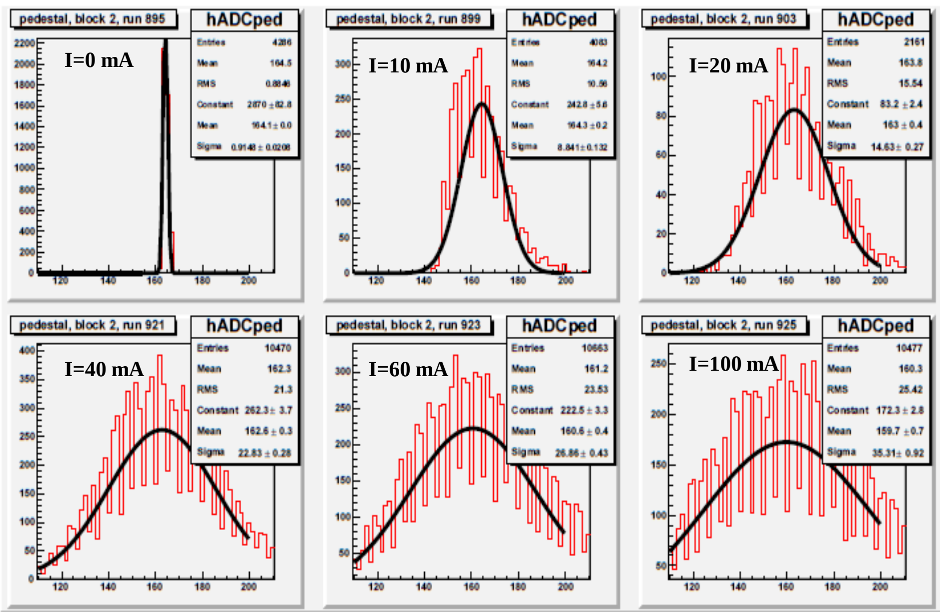
LED Holder plate



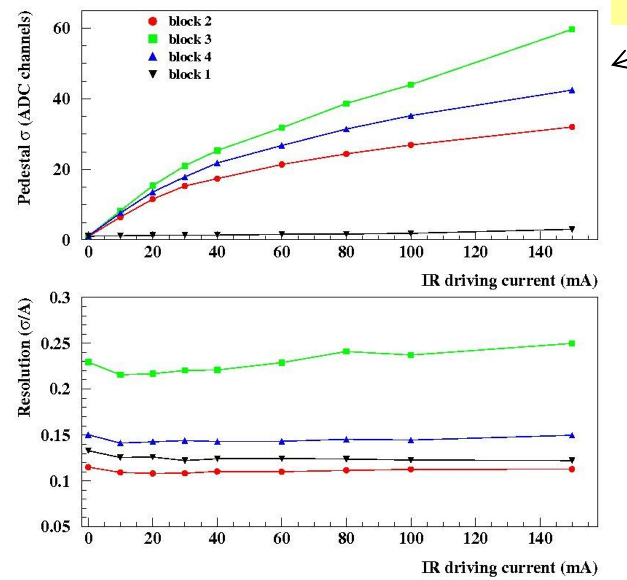
The GMS can run in parallel with data taking in wide ranges of rate and intensity.

NPS prototype: PMT sensitivity to IR light

- To quantify the effect of IR light, the prototype PMTs pedestal, and signal (generated by cosmic particle and GMS) amplitude sensitivity to the IR light intensity were studied



Crystals with 4 IR LEDs



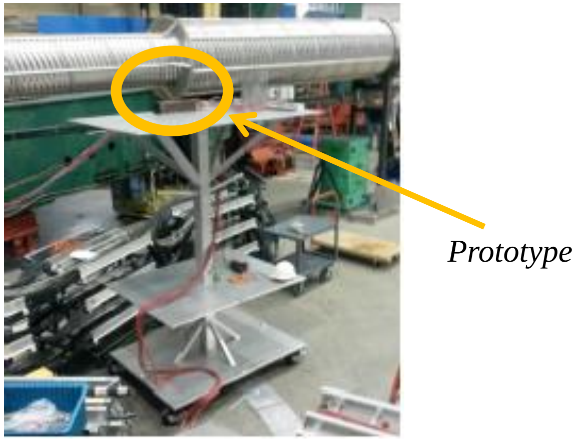
- ➢ The observed increase in signal pedestal widths suggest that the PMTs (R4125) are sensitive to IR light
- ➢ No changes in the PMTs amplitude or resolution due to IR light were observed
- ➢ There is a sharp increase in PMTs noise when the IR system runs at a driving current ~150 mA (or about 50 mA for each IR diode). The level of noise-signals at PMT high voltage of 1400 V are ~8-10 mV. The noise disappears when the IR system current is turned off

Further tests will help to fully understand how the observations of PMT sensitivity to IR light may impact its long-term stability and live-time

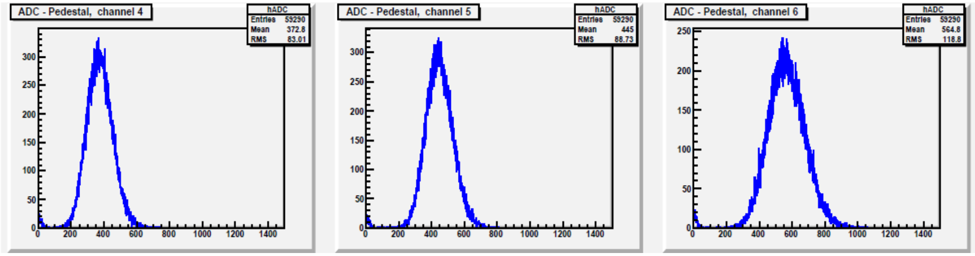
PbWO4 testing under experimental conditions

The prototype has been moved into Hall A for parasitic test in parallel with the DVCS measurements. It is installed at ~10 m from the target, at an angle ~8°, where the dose rates *~2 krad/h* are expected (adjustments in a limited range of the position is possible).

The NPS Prototype installation in Hall A. From left to right the scattering chamber, beam line, the DVCS calorimeter and the stand with Prototype can be seen.



The stand with Prototype in top and the reference tube on the middle platform.



Examples of pedestal subtracted ADC spectra from the Prototype. The GMS LED was triggered at a rate ~1 Hz, there was no beam on target.

Planned tests include:

- Monitoring the GMS generated signals from the prototype PMTs versus the accumulated doses.
    - The prototype PMT signals will be normalized to the signal from a reference PMT

PbWO4 testing at higher dose rates

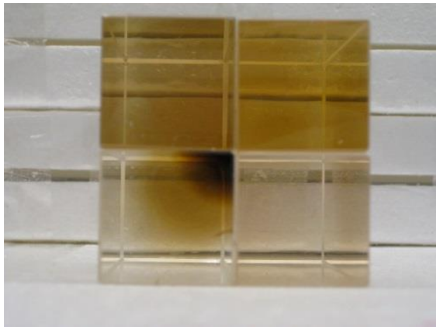
Tests for radiation damage of PbWO4 at higher dose rates are being planned at the Idaho Accelerator Center

- 20 MeV electron beam with 112 mA/pulse and repetition rate of 100 Hz

44 MeV short pulse Linac

Crystal and lead glass have been irradiated at that facility for earlier JLab experiments

- DVCS in 2009: PbF2



Example of PbF2 irradiated blocks from 2009 [J. Roche]

Beam time has been booked for February 2015

- Details of the tests to be carried out under discussion, e.g., at today's meeting

• 5 new crystals from SICCAS have been ordered for these tests, delivery expected before end of 2014.

Summary of PbWO4 and NPS Prototype Studies

- $PbWO_4$ crystals manufactured by SIC in 2000 and 2014 have been characterized
  - Transmittance of these crystals is similar and also does not seem to depend on thickness
- The $PbWO_4$ crystals were irradiated at JLab RadCon group facility up to accumulated doses of ~300 krad (dose rates 260 rad/h) – expected doses for experiments is up to ~2 Mrad
  - No notable damage to the optical properties of PbWO4 was observed within the uncertainty of the transmittance measurements
  - Radiation damage depends strongly on dose rate
- Two types of of IR LEDs were found to be suitable for the NPS IR curing system.
  - At driving current ~50 mA flux of photons is ~2×10^{16} γ/s.
  - R4125 anode current, ~0.07 mA, should not significantly shorten the PMT lifetime
- A protoype of the NPS has been constructed from 9 $PbWO_4$ crystals (2cm×2cm×20cm from SIC) and 9 PMTs R4125 (from Hamamatsu) in a copper frame
  - Includes a gain monitoring based on blue LEDs and an IR curing system consisting of three sets of IR LEDs – these can run in parallel with data taking
  - Further tests help to fully understand how the observations of PMT sensitivity to IR light may impact its long-term stability and live-time

NPS Prototype Tests and Timeline

Tests to be carried out over the next 6 months

- Test of $PbWO_4$ crystals under experimental conditions with beam using the NPS prototype in Hall A – this test will run from 2014 until end of experiment in 2015
    - Monitoring of the spectrum of the PMTs signals generated by GMS.
    - Variation of GMS light intensity will be monitored by reference PMT.
    - Monitoring of the accumulated dose (dose rates *~2 krad/h* are expected).

- Radiation damage of these crystals due to higher dose rates (>5-10 krad/hr) will be studied in February 2015 using the facility at Idaho
    - The effect of IR curing on these crystals will also be studied
    - 5 new crystals from SICCAS have been ordered for these tests, delivery expected before end of 2014.
    - Measurements of crystals transmittance before and after IR and thermal curing at 200 ^{o}C will be made

- Further studies of the impact of IR light on PMTs performance and lifetime

Backup slides

Requirements of the experiments

Parameter	**DVCS (E12-13-010)**	**DVCS (pol. 3He)**	**WACS (PR12-12-009)**	**DES π^0 (E12-13-010)**	**SIDIS π^0 (E12-13-007)**
Min. dist. From. Tgt. (m)	~3.0-6.0	~3.0-4.0	3.0-5.0	4.0	4.0
Coordinate res. (mm)	3-4	3-4	3-4	2-3	2-3
Photon angl. Res. (mrad)	1-2	1-2	1-2	0.5-0.75	0.5-0.75
Energy res. (%)	$(5\text{-}6)/\sqrt{E}$	$\sim 6/\sqrt{E}$	$\sim 5/\sqrt{E}$	$(2\text{-}3)/\sqrt{E}$	$(2\text{-}3)/\sqrt{E}$
Sweeping magnet (Tm)	0.3	0.3	0.6	0.3	0.3
Second arm	HMS	HMS	HMS	HMS	HMS
Photon angle (degrees)	6.0-23.0	6.0-25.0	22-60	10-25	6.0-23.0
Photon energies (GeV)	2.7-7.6	3-7	1.1-3.4	3.1-5.7	0.5-5.7
Acceptance (msr)	~10	~10	~10	~25	~25
Beam current (μA)	5-10	~60	~40, +6%Cu	1-2	1-2
Targets	10cm LH2	30cm 3He	15cm LH2	10cm LH2	10cm LH2
Luminosity ($cm^{-2}s^{-1}$)	$\sim 10^{38}$	$\sim 10^{37}$	$\sim 10^{39}$	$\sim 3\text{x}10^{37}$	$\sim 3\text{x}10^{37}$
Rates & Timing	~1-2MHz <100ns	~100ns	~100ns	~1-2MHz <100ns	~1-2MHz <100ns
Beam Time (hours)	~1200	~500	~1000	900	600
Expected total rad. Dose (Krad)	~200	<20	<20	~40-50	~40-50

- **Energy resolution** ➔ **high light yield, best available crystals**
- **Coordinate resolution** ➔ **fine granularity, small Møller 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**

General properties of heavy crystals for calorimetry

Parameter	Lead Tungsten (PbWO4)	Lead Fluoride (PbF2)	Bismuth Germanate (BGO)	Luterium-Yttrium (LSO/LYSO)
Density (g/cm^3)	8.28	7.66-7.77	7.13	7.2-7.4
Rad. length (cm)	0.89	0.93-0.95	1.10-1.12	1.16
Refraction index	2.20	1.82	2.15	1.82
Emission peak (nm)	420	~310, ~280	480	420
Moliere radius (cm)	2.19	2.22	2.15	2.07
Radiation type	Scint. (~13% Č)	Pure Čer.	Scint. (~1.6% Č)	Scintillation
Timing property τ (ns, %)	5(73%), 14(23%), 110(4%)	Fast, <30	300	40-50
Effective Z	73	77	83	65
Hydroscopicity	No	No	No	No
Interact. length (cm)	~20.7	~21	~22.7	~20.9
Rad. hardness (krad)	~20-50	~50	~1,000	>1,000
Light yield LY (photon/MeV)	~140-200	~2-6	~5,000-10,000	~5,000-30,000
d(LY)/dT (%/°C)	-2.0-2.5	No	-0.9	-0.2
Critical energy (MeV)	~9.6	8.6-9.0	7.0	9.6

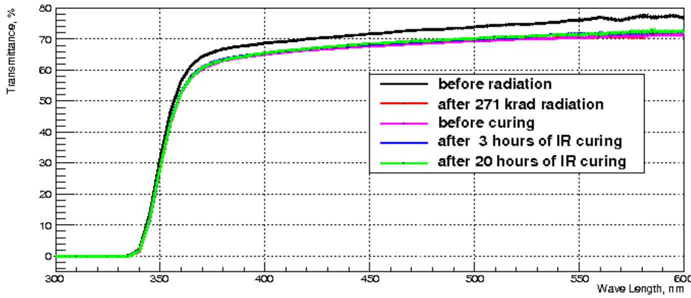
BGO, $PbWO_4$, PbF_2 and LSO/LYSO are among the good candidates

But BGO is too slow and LSO/LYSO are very expensive.

Our choice would be to use $PbWO_4$ or PbF_2, or their combination

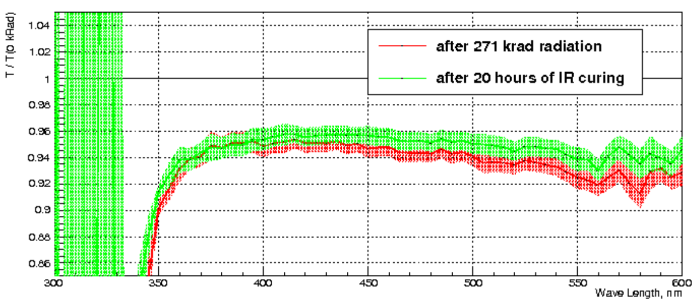
Test of IR curing of PbWO4 crystals

- One of the crystals (3x3x18 cm^3, BTCP/SIC) irradiated with dose rate 260 rad/h was cured by IR light with λ=940 nm (generated by a set of 4 TCAL-7400 LEDs).
  - No definite sign of IR curing was observed



Transmittance in transverse direction at 8 mm distance from the radiated end, before and after IR curing.

- Note that for this crystal showed a very weak effect of possible radiation damage (~2% after accumulated dose ~270 krad)
  - Given the current accuracy of the measurement this may be too small of an effect to determine if actual radiation damage was observed



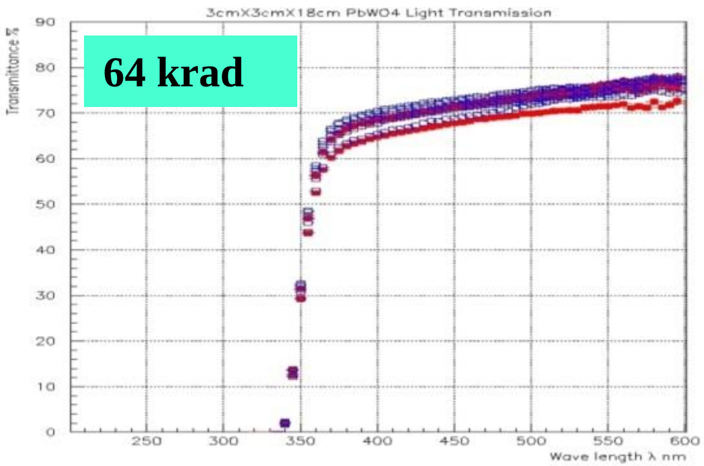
Ratio of transmittance before and after 271 krad radiation and 20 hrs of IR curing

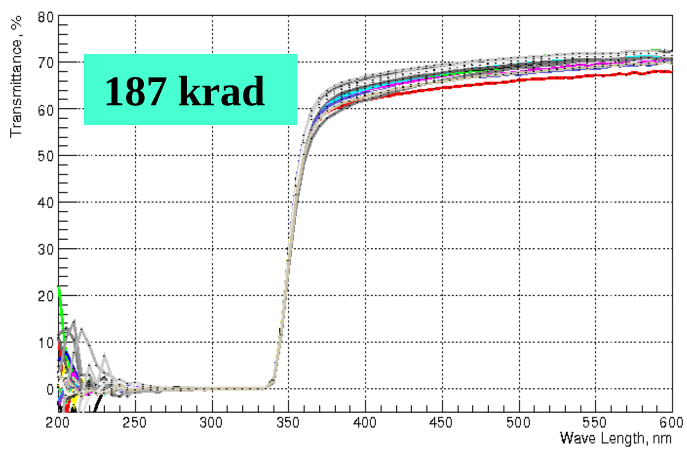
- To test the effectiveness of IR curing a definite sign of radiation damage has to be observed. This could be achieved by:
  - Irradiation at higher dose rates
  - Further improving accuracy of setup

Crystal Characterization: Irradiation with up to ~300 krad accumulated doses

- A 3×3×18 cm³ crystal (produced in 2000 by BTCP/SIC for CMS) was radiated by γ-source from one end (longitudinally), to 64 krad, 187 krad and 271 krad accumulated doses.

- Data show significant point-to-point variation, but no change in the optical performance up to ~300 krad integral dose within the uncertainty of the measurement





The transmittance was measured at 2-100 mm distances from the radiated end, in the transverse direction.