Status of R&D on the Inner Crystal Calorimeter for EIC (part of eRD1)

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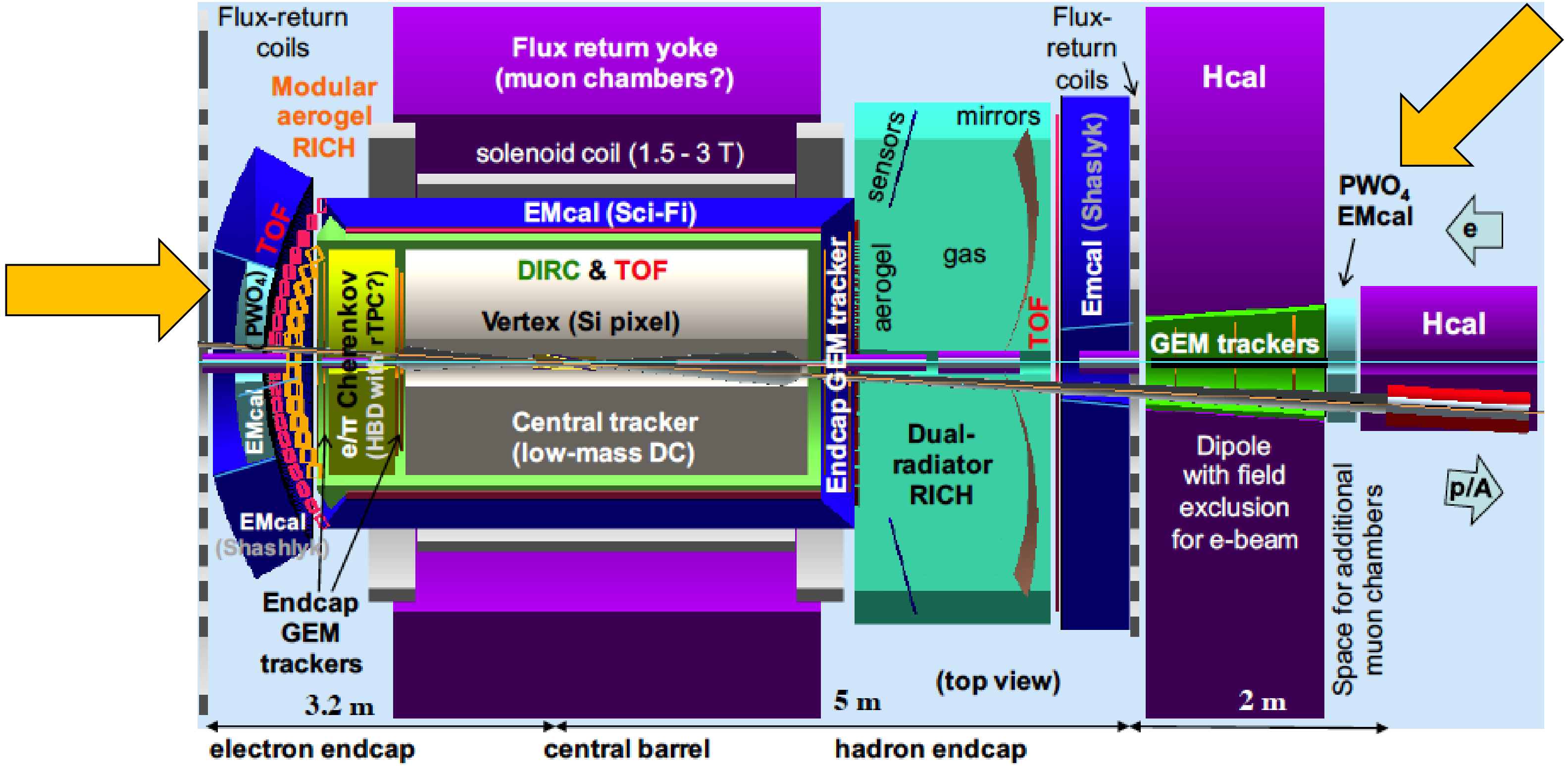
High resolution calorimetry for endcaps

- PID requirements in the electron endcap primarily driven by semi-inclusive and exclusive processes, e.g., DVCS
- PID requirements in the ion endcap primarily driven by exclusive processes, e.g., DVCS (γ vs. photons from π^0 decay) and to detect excitation in recoil baryons

Detection at very small angle is needed

Example: JLEIC detector



High resolution calorimetry – functions and requirements

- EM calorimetry has two main functions
  - Particle IDentification: important for discriminating single photons from, e.g., π^0 decay and e/p
  - Particle Reconstruction: driven by need to accurately reconstruct the four-momentum of scattered electrons at small angles, where the momentum (or energy) resolution from the tracker is poor.

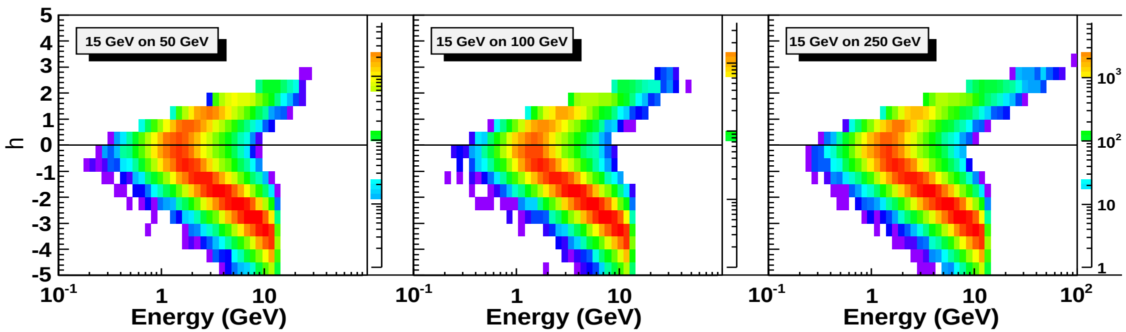
- EM Inner Calorimeter Requirements
  - Good resolution in angle to at least 1 degree to distinguish between clusters
    - **Ex: DVCS – see next slide**
  - Energy resolution to a few %/sqrtE for measurements of cluster energy
    - Resolution helps to extend useful y-range, "purity" in x/Q^2 bins
  - Ability to withstand radiation down to at least 1 deg wrt beam line

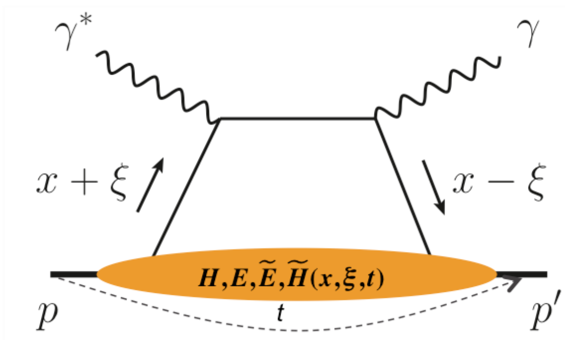
Example: Exclusive Reactions - DVCS

Slide from E. Aschenauer, EIC UG meeting Jan. 2016

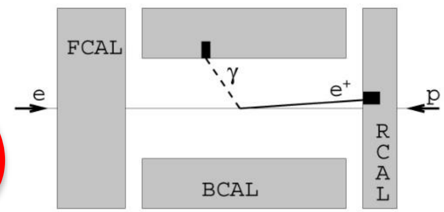
DVCS – photon kinematics:

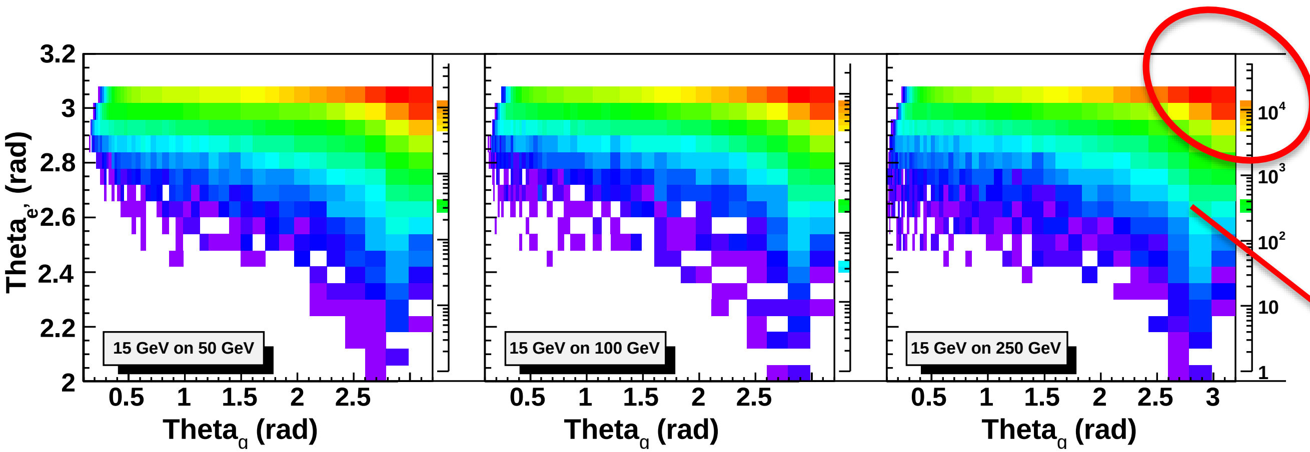
Cuts: Q^2>1 GeV, 0.01<y<0.85

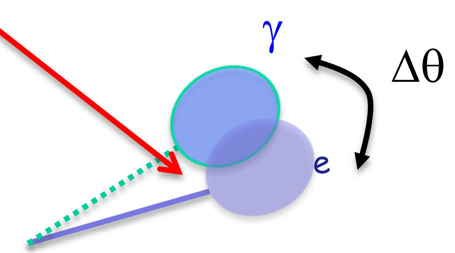




increasing Hadron Beam Energy influences max. photon energy at fixed η photons are boosted to negative rapidities (lepton direction)





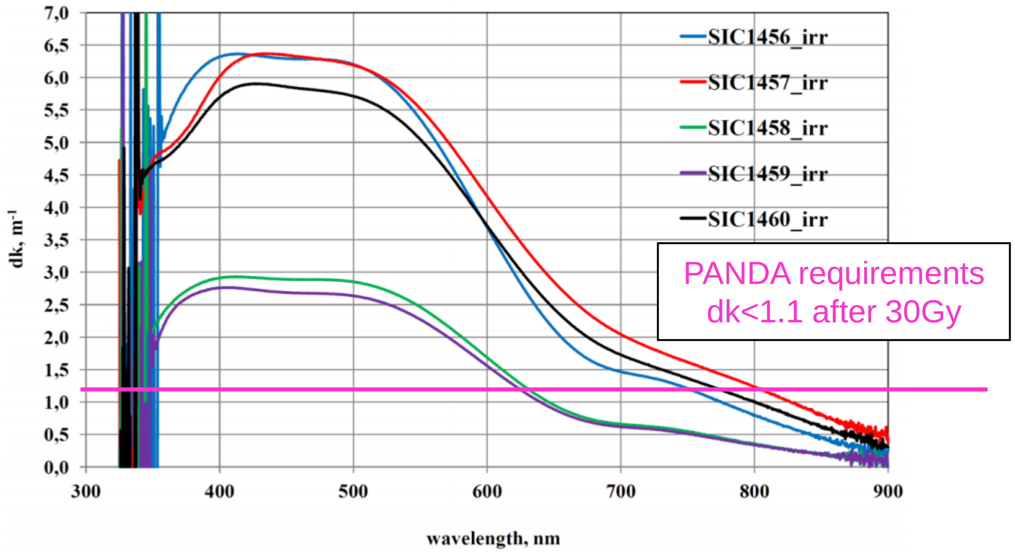


ECal granularity: need to be able to distinguish clusters down to Δθ=1º

High resolution calorimetry based on $PbWO_4$ crystals

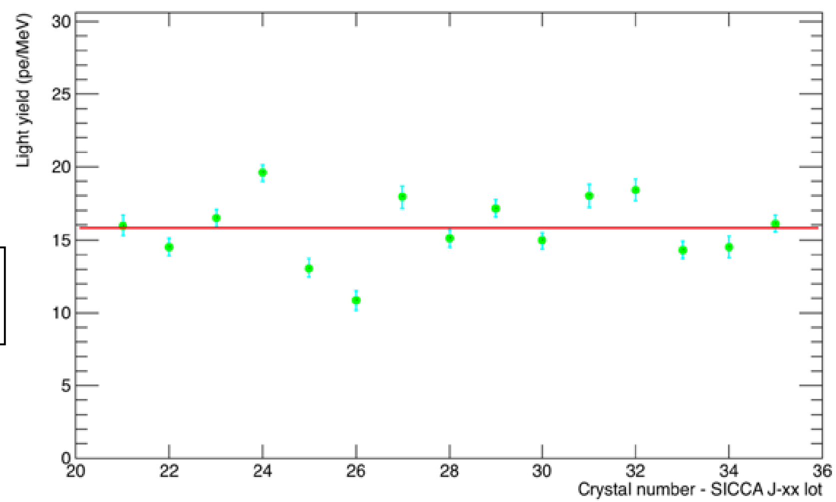
- $PbWO_4$ has been extensively used for high precision calorimetry (CMS, JLab, PANDA…) because of its energy and time resolutions and its radiation hardness.
- BTCP (Russia) produced high quality crystals in the past using the Czochralsky growing method, but it's now out of business.
- SICCAS (China) uses the Bridgeman method - problems maintaining good crystal quality. Need to develop process towards acceptable crystals quality assurance towards EIC needs.
- Need to develop an alternate supplier of $PbWO_4$ in order to ensure worldwide availability of high quality crystals (potential candidate: CRYTUR, Czech Republic).

$$dk = \frac{\ln(T_{bef}/T_{aft})}{D}$$ Radiation induced absorption coefficient



Radiation hardness of recent SICCAS crystals

Light yield: large variations crystal to crystal



What was planned for FY16

Need to develop process towards acceptable crystals quality assurance towards EIC needs.

- Setup infrastructure for crystal testing at CUA and IPNO, and understand systematic effects in characterization of 2014/15 SICCAS produced crystals

Need to develop an alternate supplier of $PbWO_4$

- Procure a reasonable batch of full-sized crystals from CRYTUR to evaluate crytal-to-crystal variation

Need to cross check system performance of acceptable crystals.

- Construct a prototype to study actual energy and position resolution of SICCAS or CRYTUR crystals with test beam and test a SiPM-based readout system

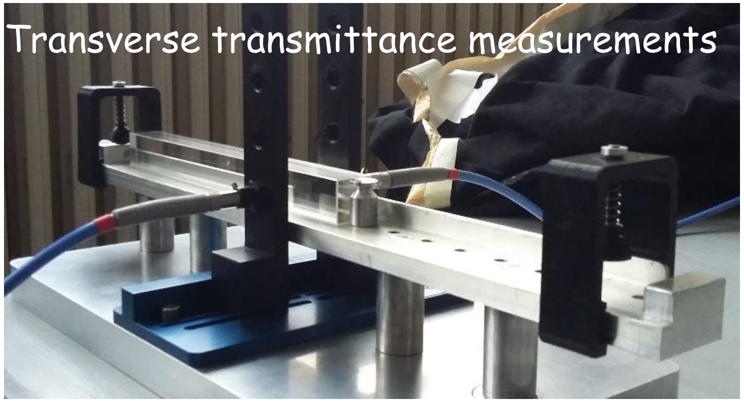
What was achieved in FY16

- The actual FY16 budget was 21% ($12K) of the requested budget
  - With these constraints our activities were limited... However, with commitment of internal university and laboratory funds and through synergy with the Neutral Particle Spectrometer (NPS) project at Jlab, we managed to make some progress:
    - Partially setup crystal testing infrastructure at CUA and IPNO
      - initial studies towards understanding crystal-to-crystal variations and systematic effects
    - Procured three full-sized CRYTUR crystals
      - initial measurements of full-sized CRYTUR crystals – reliable studies of crystal-to-crystal variation not possible with three crystals
    - No substantial progress on prototype studies
      - Some progress in design optimizations based on the smaller prototype for the NPS at JLab

Setting up infrastructure for crystal testing

IPN-Orsay (France) – proximity to Giessen U. and CRYTUR

- ❑ Optical Transmittance (L/T)
  - Fiber-based spectrometer
  - Setup was commissioned with BTCP crystals on loan from Giessen
- ❑ Crystal light yield and timing
  - A setup is currently being tested with cosmic rays

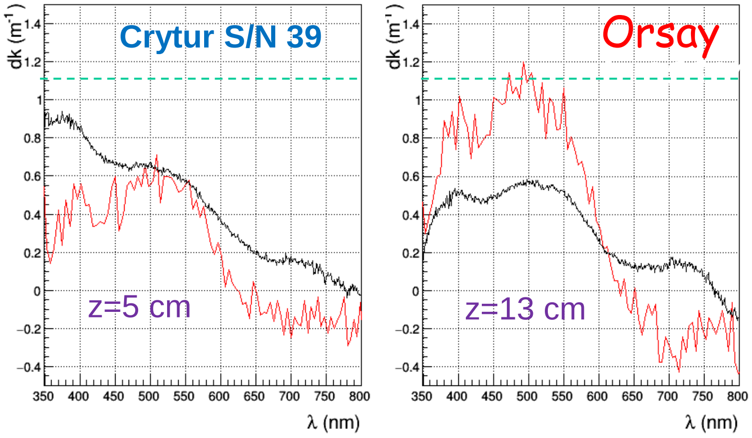


Laboratoire de Chimie Physique (Orsay)

- ❑ Radiation Hardness
  - Strong ^{60}Co sources available at LCP-Orsay
  - Initial tests performed on June 23

Radiation induced coefficient at different transverse positions

Integral dose = 30 Gy

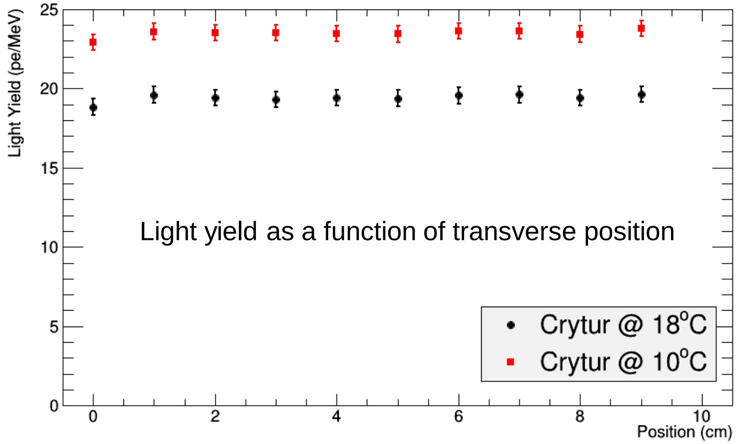


- ALTO at IPN-Orsay:
  - 50 MeV electrons up to 1uA
  - Proton beam (Tandem) also available

Setting up infrastructure for crystal testing

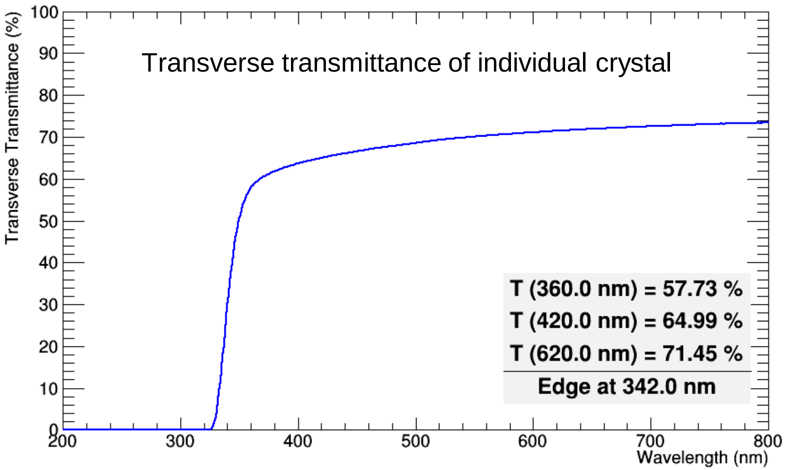
The Catholic University of America

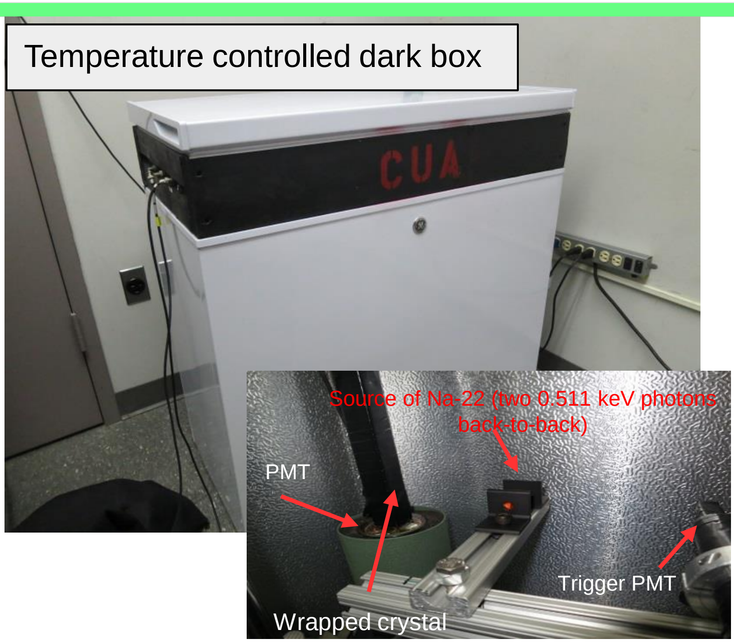
CUA (USA) – proximity to JLab, SICCAS crystals

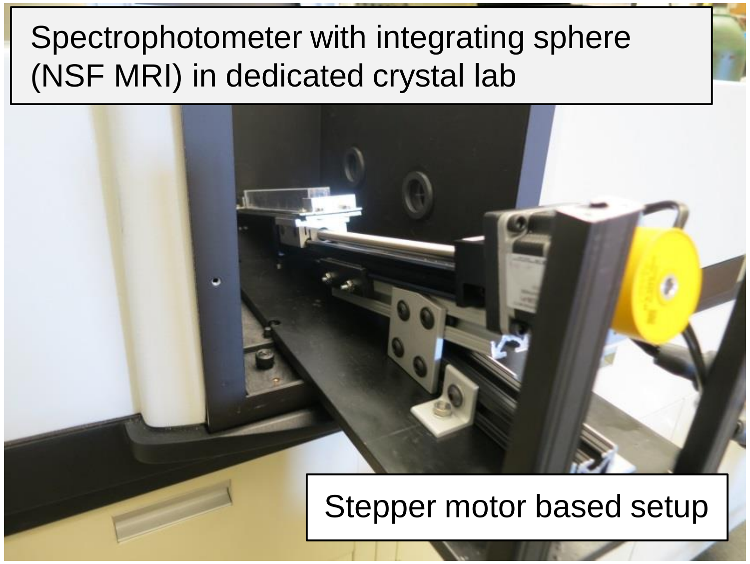


Comparison with Giessen measurement at 18°:

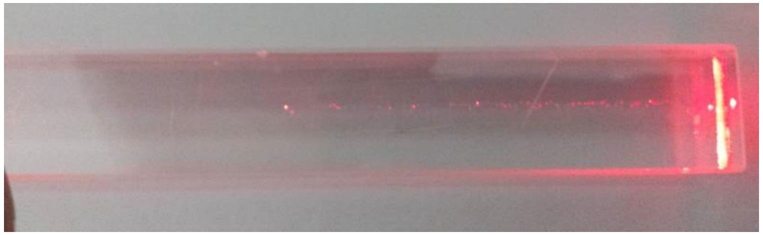
- CUA: 19.4 +/- 0.7 pe/MeV
- Giessen: 19.2 pe/MeV







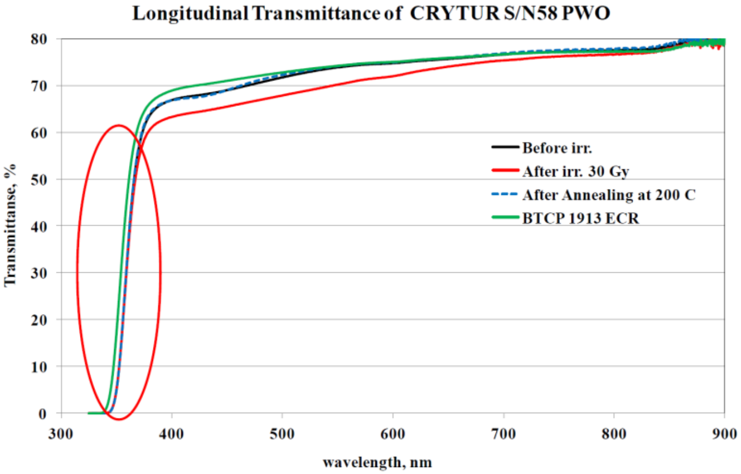
Test of recent CRYTUR crystals – through collaboration with NPS project at JLab

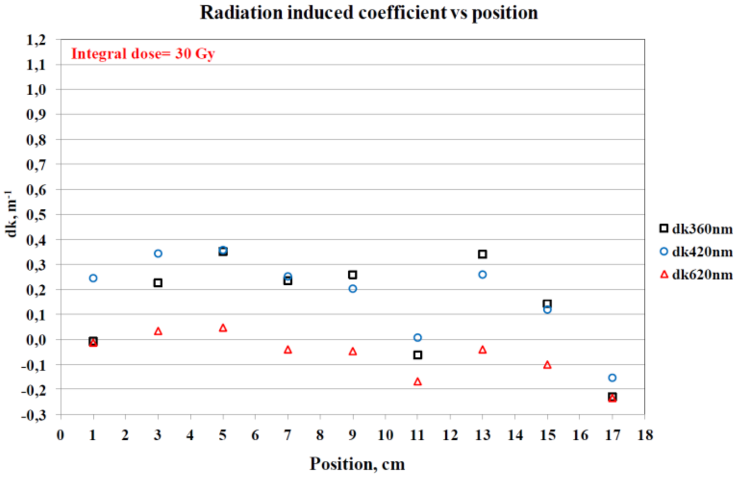


First full size (2x2x20 cm^3) crystal produced by CRYTUR (Oct 2015)

Grown in Ar atmosphere & doped with La+Y

- 3 new (2016) crystals from CRYTUR with dimensions: 20x20x18.5 mm^3
- Low light yield (12-13 pe at 18°), with tolerable non-uniformity (maybe due to high doping)
- Acceptable transmittance. Longitudinal transmittance **does not** show absorption band in the luminescence range
- Crystal similar to CMS quality (shift of transmittance edge and low radiation induced coefficient)





V. Dormenev

Funding Request (FY17)

- Main priorities – complete FY16 activities (that were not funded in FY16)
  - Quantify crystal-to-crystal variation of SICCAS crystals and possibly understand their origin – provide a measure of the quality that can be achieved by the vendor
    - In anticipation of the next crystal testing phase and with support from universities and laboratories CUA and IPNO have been actively procuring components and allocating space
  - Procure 10 more full-sized crystals from CRYTUR to do a reliable evaluation of crystal-to-crystal variation
    - Quantify impact of systematic uncertainties between measurements at different institutions
  - Prototype to study actual energy and position resolution of crystals with beam
- Assuming FY16 activities completed successfully, R&D will focus on optimization of geometry, cooling, choices of readout

External Funding

- All of the FTEs required for working towards finalizing the crystal test setup and crystal characterization are provided by CUA/IPNO or external grants. The absence of any labor costs makes this proposed R&D effort extremely cost effective.
  - Nine people working on project – additional collaborators at JLab, Giessen University, Yerevan, VSL@CUA

- The 2014 and 2015 SIC crystals are provided through synergistic activities with independent research for the Neutral Particle Spectrometer (NPS) project at JLab.

- The expertise and use of specialized instruments required for crystal characterization and their chemical analysis, as well as additional crystals samples are made possible through collaboration with the Vitreous State Laboratory (VSL) at CUA that is also collaborating on the NPS project.

- Similarly, the work highly benefits from support groups within IPN Orsay and the expertise provided by Giessen University.

Funding Request (FY17)

- Critical issue: complete FY16 activities (that were not funded in FY16)

Item	**FY17**	**FY18**
Procure crystals from Crytur	40	
Crystal tests including radiation	10	
Technical support	5	15
Prototype	10	
Travel	5	15
Cooling system		30
Readout system		40
TOTAL	**70**	**100**

Summary

- Potentially 2 vendors available for PWO crystals:
  - SIC show quality control instabilities
  - Crytur making very good progress towards mass production capabilities
- Infrastructure being developed at CUA and IPNO for crystal quality control
- Prototype being constructed for beam test

Publications and Talks

- C. Munoz-Camacho et al.. “R&D for high resolution calorimetry at the future Electron-Ion Collider”, Presentation at the XVIIth International Conference on Calorimetry in Particle Physics, 15-20 May 2016, Daegu, South Korea
- T. Horn et al., J. Phys. Conf. S. 587 (2015) 1, 012048
- T. Horn et al., presentation at the APS DNP 2015 fall meeting, Santa Fe, NM

Students

- Salina Ali (CUA)
- Marco Carmignotto (CUA)
- William Lash (CUA)
- Frederic Georges (IPN-Orsay)

PWO crystal specifications

Parameter	*Unit*	*CMS PWO-I*	*PANDA PWO-II*	*EIC*
Luminescence maximum	nm	420	420	420
Expected energy range of EMC	GeV	0.15-1000	0.01-10	0.1-15
Light Yield at RT	phe/MeV	8.0	16.0	15?
EMC operating temperature	°C	+18	-25	
Energy resolution at 1 GeV	%	3.4	2.0	few %/√E
LY(100ns)/LY(1us)		0.9	0.9	
Optical transmission at 360 nm	%	25	35	
Optical transmission at 420 nm	%	55	60	
Optical transmission at 620 nm	%	65	70	
Homogeneity at T=50%	nm	3.0	3.0	
Induced absorption coefficient k at RT, >100 Gy/hr	m^{-1}	1.6	1.1	1.5?
Mean value of k	m^{-1}		<0.75	