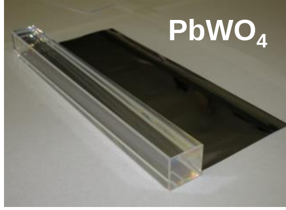
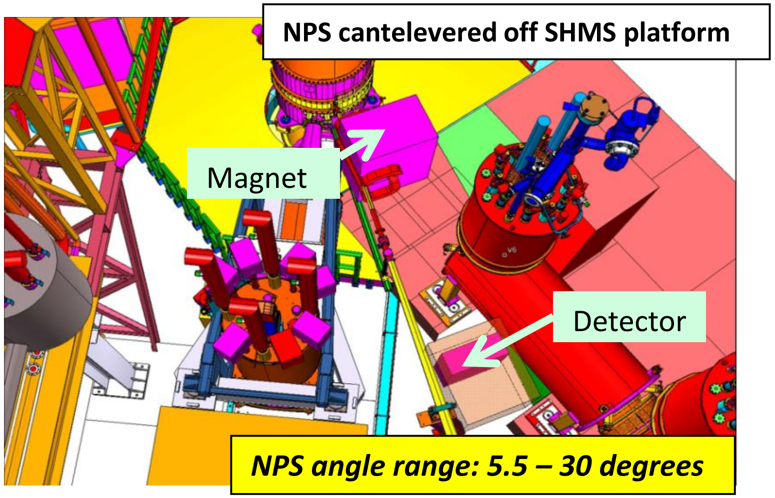
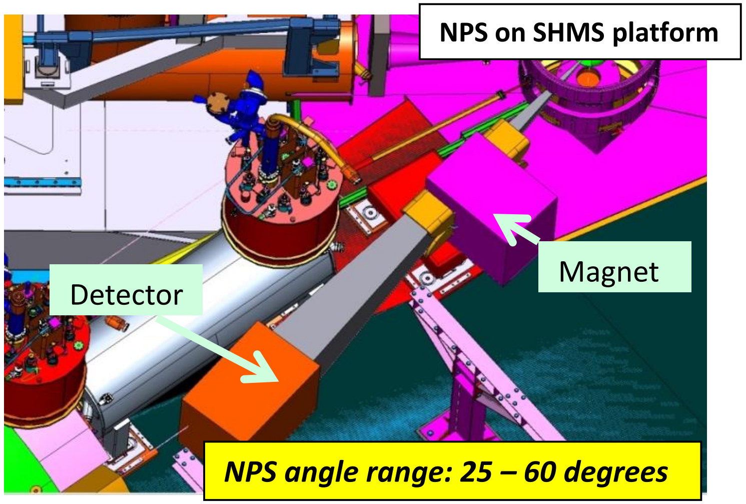
The Neutral-Particle Spectrometer (NPS)



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





- Global design of a neutral-particle spectrometer between 5.5 and 60 degrees consists of a highly segmented EM calorimeter preceded by a sweeping magnet

NPS Collaboration

I. Albayrak, J. R.M. Annand, A. Asaturyan, M. Boer, A. Camsonne, M. Carmignotto, D. Day, D. Dutta, R. Ent, M. Guidal, D.J. Hamilton, N. Hlavin, T. Horn, C. Hyde, H. Mkrtchyan, D. Keller, C. Keppel, E. Kinney, F. Klein, A. Mkrtchyan, C. Munoz-Camacho, P. Nadel-Turonski, R. Paremuzyan, H. Rashad, J. Roche, O. Rondon, I. Sapkota, S. Sirca, V. Tadevosyan, B. Wojtsekhowski, S. Wood, S. Zhamkochyan, J. Zhang, C. Zorn

A.I. Alikhanyan National Science Laboratory/Yerevan, Catholic Univ. of America/USA, Institut de Physique Nucleaire d'Orsay/France, Univ. of New Hampshire, Univ. of Colorado, Mississippi State Univ./USA, Jefferson Laboratory/USA, Ohio University/USA, Old Dominion Univ./USA, Univ. of Glasgow/Scotland, Univ. Ljubljana/Slovenia, Akdeniz Univ./Turkey, Univ. of Virginia/USA

Overview Scientific Program

- 5 experiments approved by PAC (40, 42) to date
  - E12-13-007: Measurement of Semi-inclusive π^0 production as Validation of Factorization
  - E12-13-010 – Exclusive Deeply Virtual Compton and π^0 Cross Section Measurements in Hall C
  - E12-14-003 – Wide-angle Compton Scattering at 8 and 10 GeV Photon Energies
  - E12-14-005 – Wide Angle Exclusive Photoproduction of π^0 Mesons
  - E12-14-006 – Initial State Helicity Correlation in Wide-Angle Compton Scattering

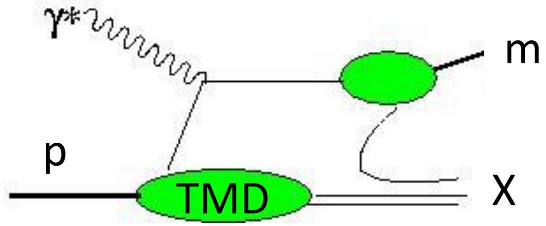
- 1 LOI and one proposal submitted to PAC43 in 2015
  - LOI12-15-007 – Timelike Compton Scattering with transverse target
  - PR12-15-003 – Double Polarization Observables in WACS at Photon Energies up to 8 GeV

- Ideas exist for future experiments and new scientific directions taking advantage of the compatibility of NPS with Hall infrastructure
  - DVCS with polarized targets
  - Exploring possibilities for correlation experiments
  - …

E12-13-007: basic (e,e'π) cross sections

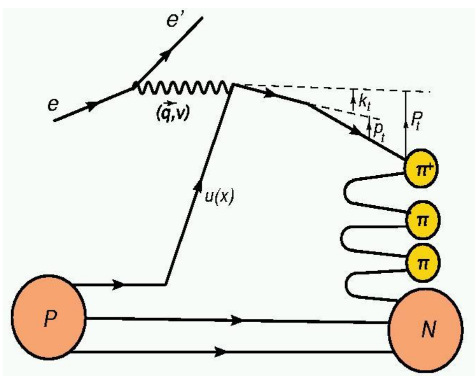
Linked to framework of *Transverse Momentum Dependent Parton Distributions*

- Validation of factorization theorem needed for most future SIDIS experiments and their interpretation
- Need to constrain TMD evolution w. precision data
- Questions on target-mass corrections and ln(1-z) resummations require precision large-z data



$TMD^q(x,k_T)$

Transverse momentum widths of quarks with **different flavor (and polarization)** can be different



$P_T = p_t + z\,k_t + O(k_t^2/Q^2)$

E12-13-007 goal: Measure the basic SIDIS cross sections of π^o production off the proton, including a map of the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV), to validate(*) flavor decomposition and the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

Requires new ~25 msr Neutral-Particle Spectrometer

Advantages of (e,e'π^o) beyond (e,e'$\pi^{+/-}$)

- Many experimental and theoretical advantages to validate understanding of SIDIS with neutral pions
- Can verify: $\sigma^{\pi^o}(x,z) = ½\,(\sigma^{\pi^+}(x,z) + \sigma^{\pi^-}(x,z))$
- Confirms understanding of flavor decomposition/k_T dependence

PAC: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon."

E12-13-010: Towards the 3D Structure of the Proton

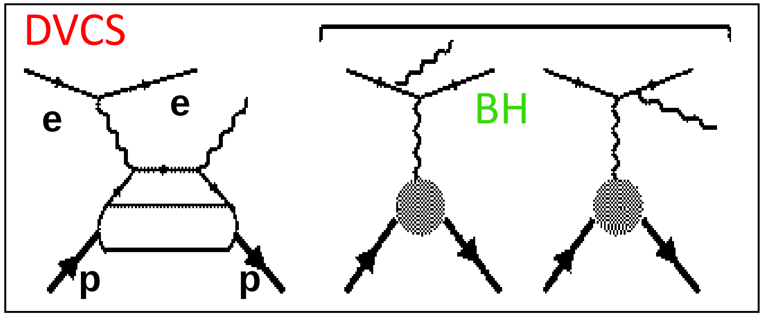
Simplest process: **e + p → e' + p + γ (DVCS)**

E12-13-010 DVCS measurements follow up on measurements in Hall A:

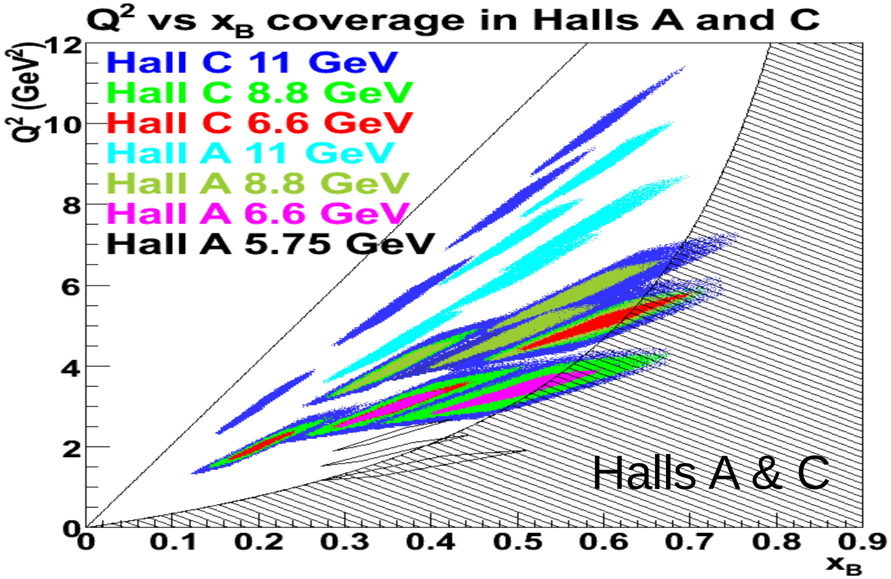
- Scaling of the Compton Form Factor
- Rosenbluth-like separation of DVCS:

$$\sigma = |BH|^2 + \mathrm{Re}\left[\underbrace{DVCS^{\perp}\, BH}_{\sim E_{beam}^2}\right] + \underbrace{|DVCS|^2}_{\sim E_{beam}^3}$$

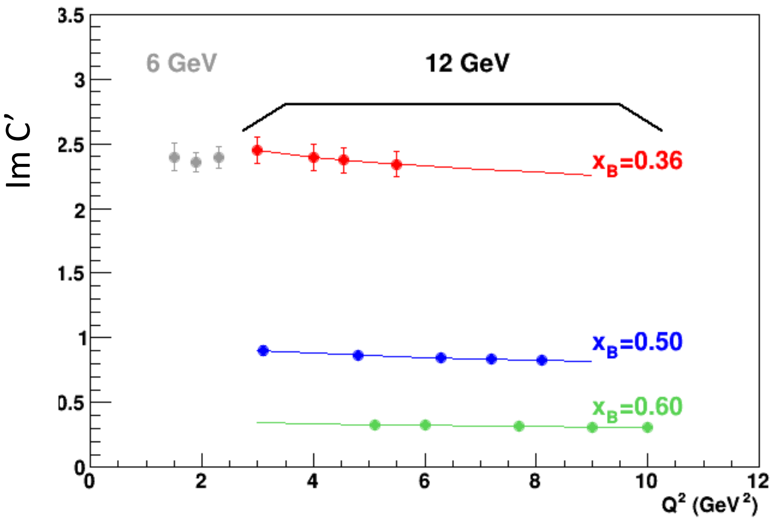
- L/T separation of π^o production



Hall A data for Compton form factor (over *limited* Q^2 range) agree with hard-scattering



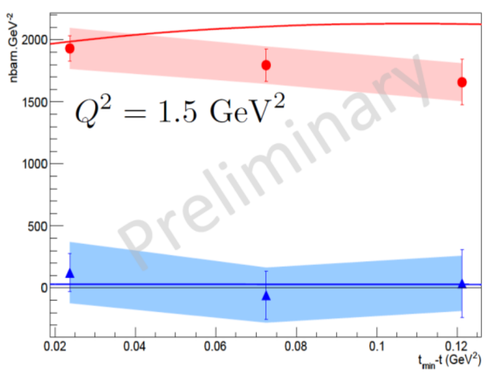
12 GeV projections: confirm formalism

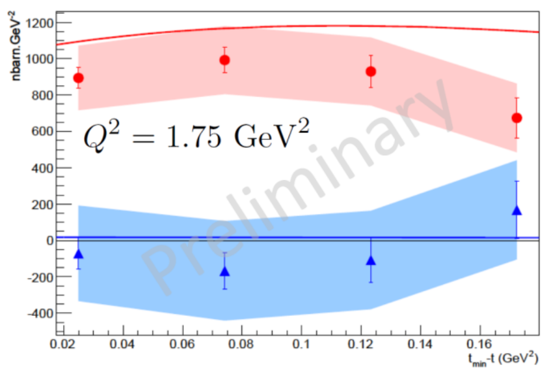


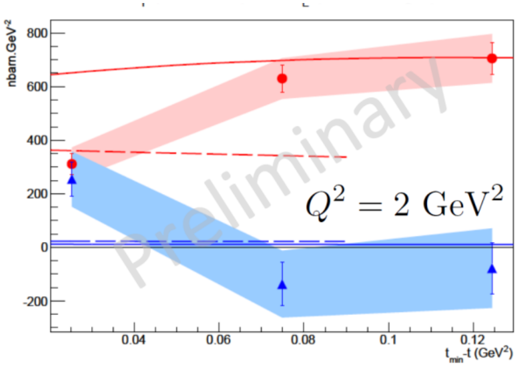
Extracting the real part of CFFs from DVCS requires measuring the cross section at multiple beam energies (DVCS^2–Interference separation)

E12-13-010: Exclusive π^0 cross section

- Relative L/T contribution to π^0 cross section important in probing transversity
  - If σ_T large: access to transversity GPDs
- Preliminary results from Hall A at 6 GeV Jlab suggest that the longitudinal cross section in π^0 production is non-zero at Q^2~2GeV^2
- Q^2/t dependence complicates final conclusion on dominance of σ_T





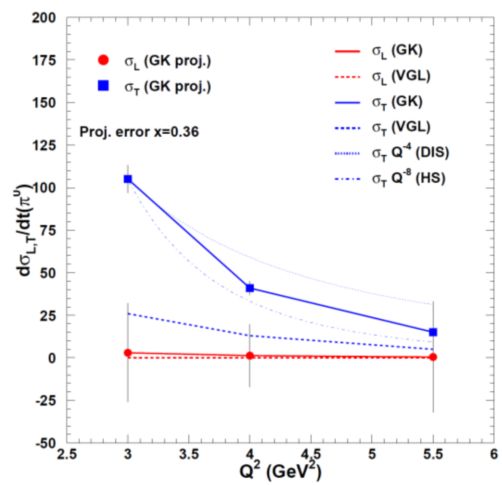


red circle=σ_L, blue triangle=σ_T

[M. Defurne, talk at DIS2015]

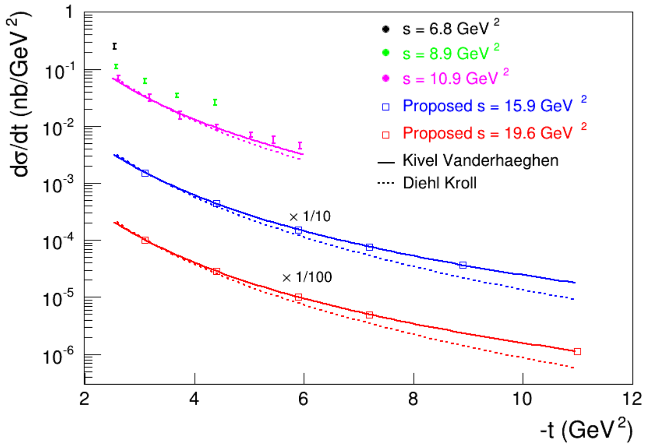
[F. Sabatie, talk at CIPANP2015]

[E12-13-010 projections]



E12-13-010 will provide essential data on σ_T and σ_L at higher Q^2 for reliable interpretation of 12 GeV GPD data!

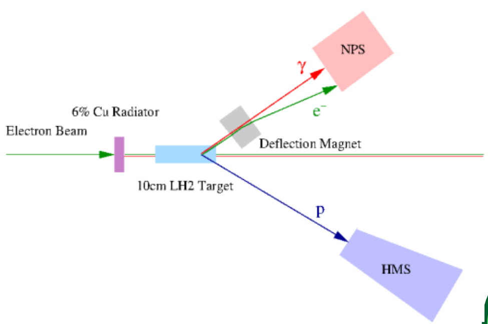
E12-14-003: WACS - the process of choice to explore factorization in wide-angle processes

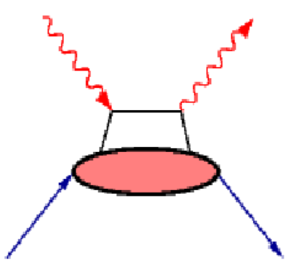


- WACS is a powerful probe of nucleon structure -several theoretical approaches developed in recent years.
  - Developments within the Soft Collinear Effective Theory (SCET) demonstrated importance of future data for interpretation of a wide variety of hard exclusive reactions.

- JLab Hall A data suggest factorization into hard and soft-collinear parts (but limited in -t).

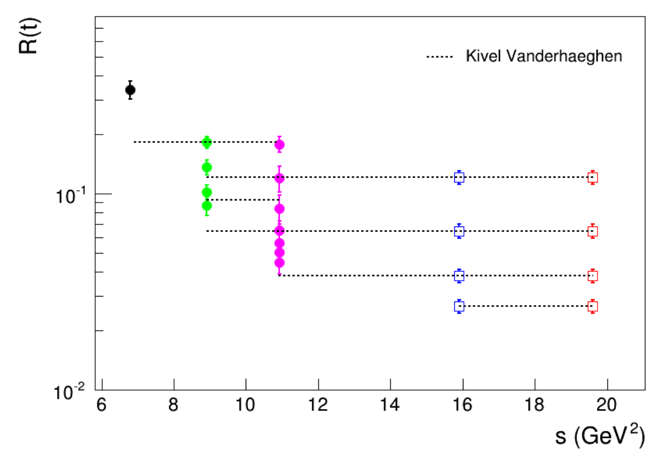
- E12-14-003 will use the Hall C HMS and the new **Neutral Particle Spectrometer** to measure the differential cross section



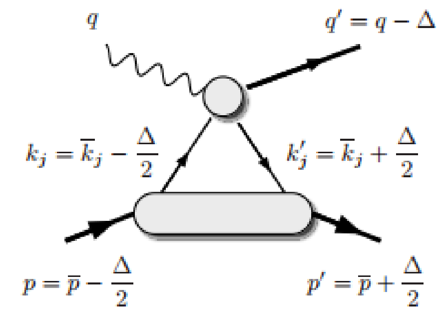


Two main goals of E12-14-003

- Four fixed -t scans will allow for a rigorous test of factorization.
- The t-dependence of the Compton form factor will allow us to gain valuable insights into proton structure at high momentum transfer.

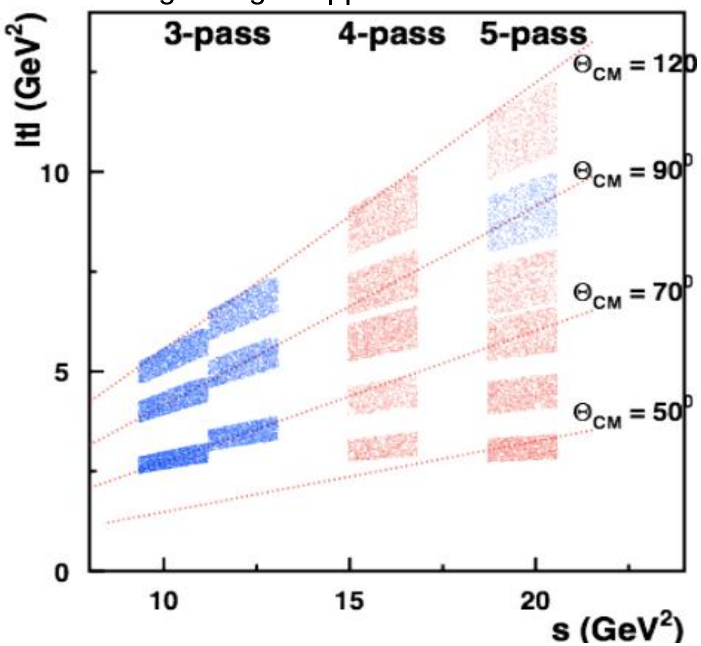


E12-14-005: Wide-Angle exclusive photo-production of π^0 mesons

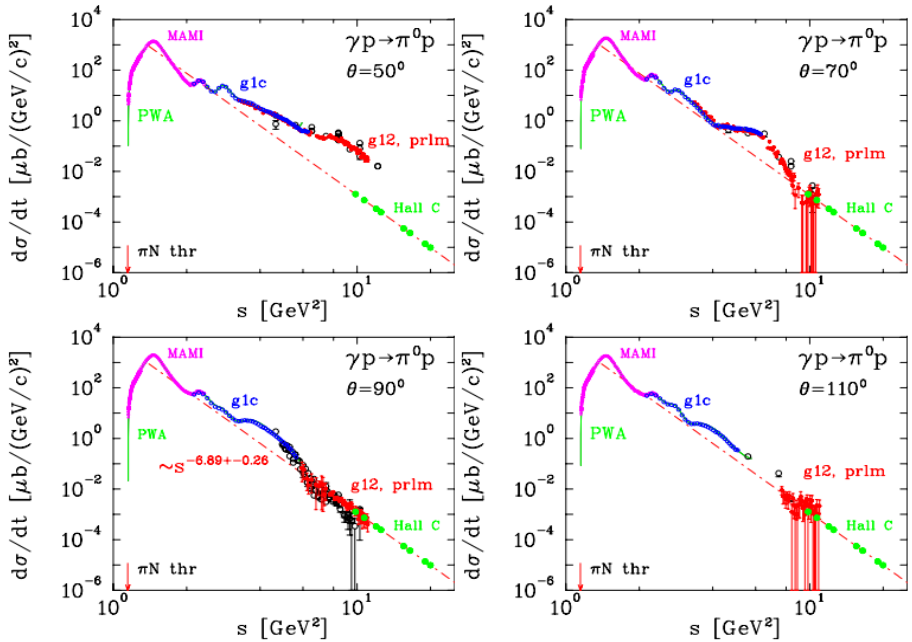


The next simplest reaction after Compton scattering, but model predictions disagree with data by orders of magnitude!

Using the NPS E12-14-005 will cover a large range in |t| and s



E12-14-005 projections



E12-14-005: basic cross section to confirm scaling and provide wide angular coverage for testing models based on the dominance of handbag mechanism.

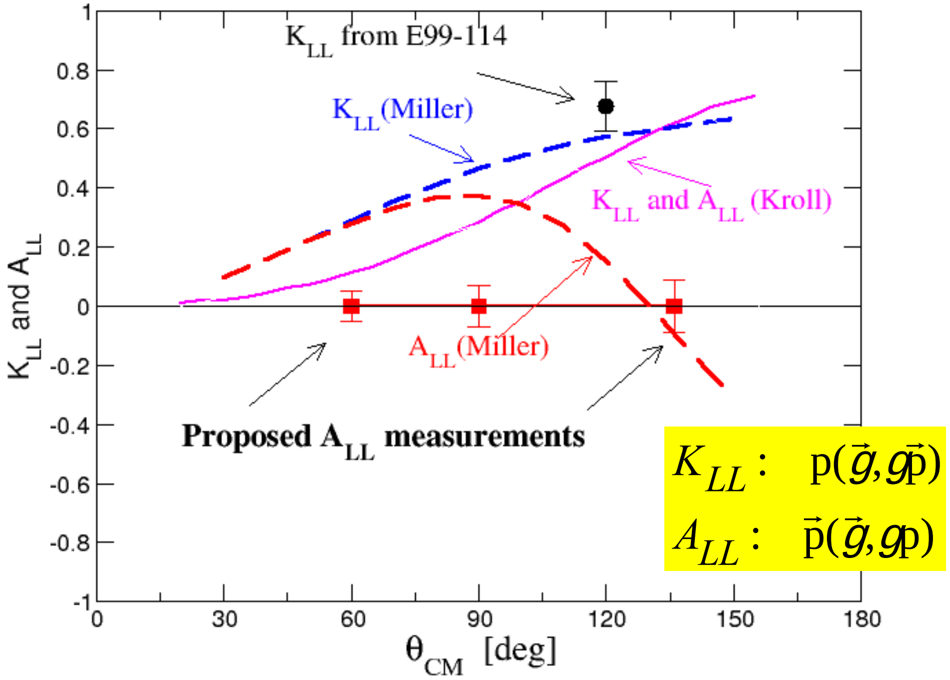
Also help with extracting Regge trajectories

E12-14-006: Polarization observables in WACS

- Polarized WACS allows for studies of the size of *power-suppressed corrections* in the reaction mechanism due to, e.g., quark mass effects in a constituent quark model framework or to dressed-quark mass effects

- Jlab data on recoil obervable K_{LL} indicate partonic mechanism

- Theoretical models do not describe the data well
  - GK: Elementary quarks, x ~ 1 kinematic approx.
  - Miller: Constituent qqq wave function; Good fit to Elastic G_E, G_M



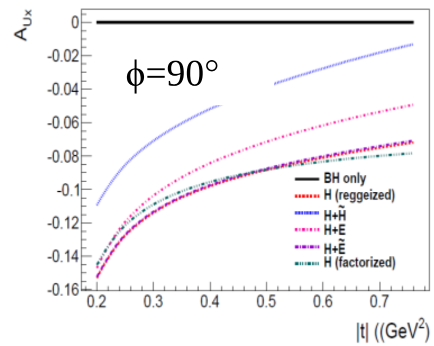
E12-14-006: measurements of target polarization observable A_{LL}

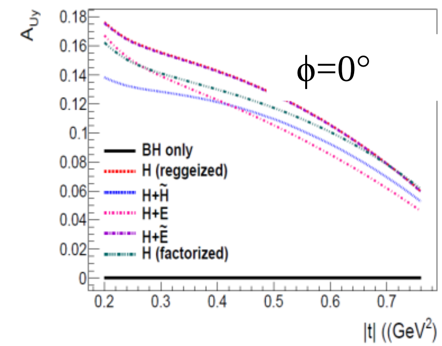
- Any difference between A_{LL} and the recoil observable K_{LL} is indicative of the scale at which one approaches the leading order partonic mechanism

Timelike Compton Scattering with Transverse targets

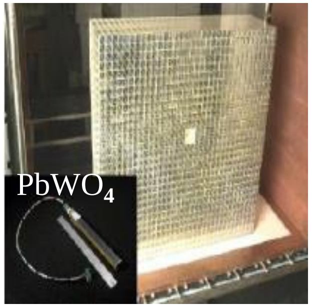
LOI12-15-007

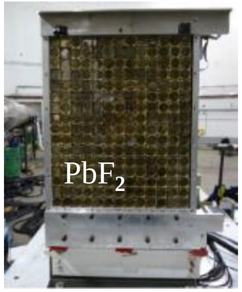
- Features of TCS measurements with transversely polarized target
  - Theoretical calculations show that transverse asymmetries are very sensitive to GPDs *[M. Boer, M. Guidal, arXiv:1412.2036]*
  - Asymmetries for the BH the main background for TCS is zero
  - Predictions for asymmetries with different assumption of GPDs vary up to 20%

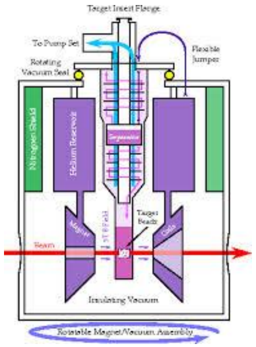




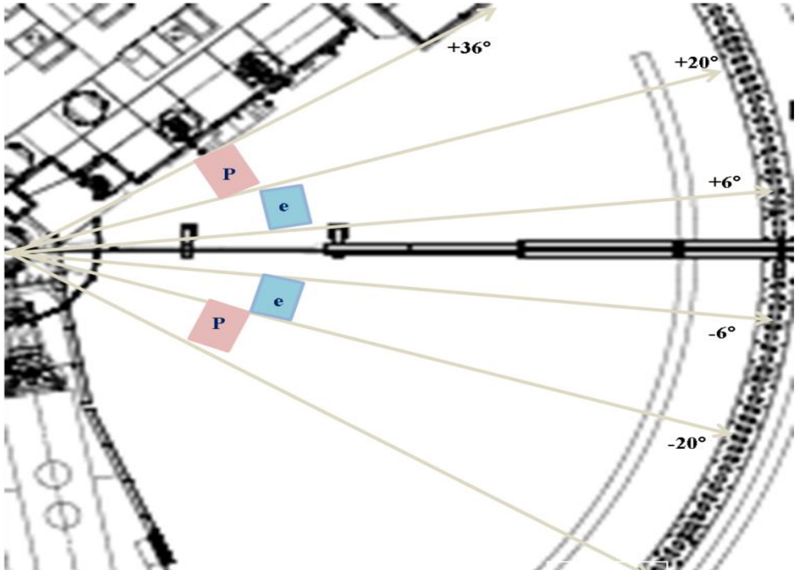
- TCS event detection with NPS
  - Lepton pair will be detected by pair of NPS
  - Recoil detection by combination of tracking and TOF







NH_3 Target

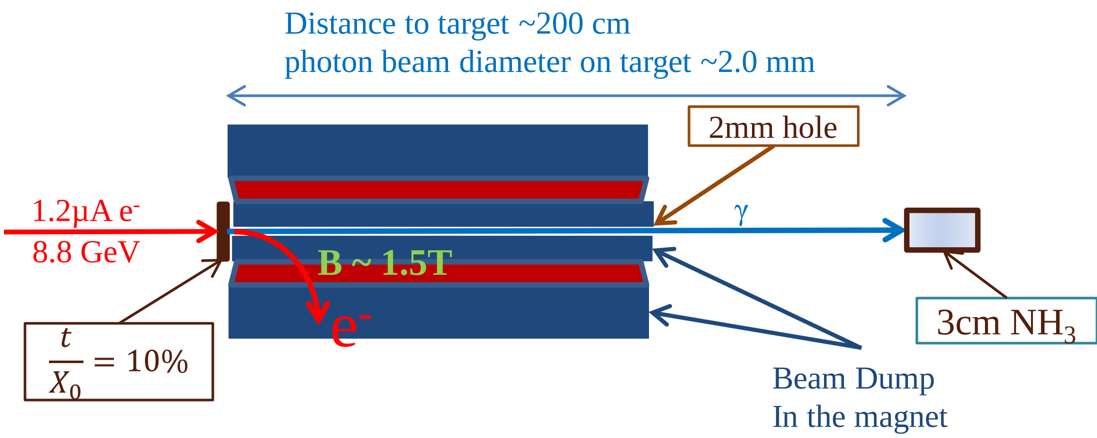


Hall C

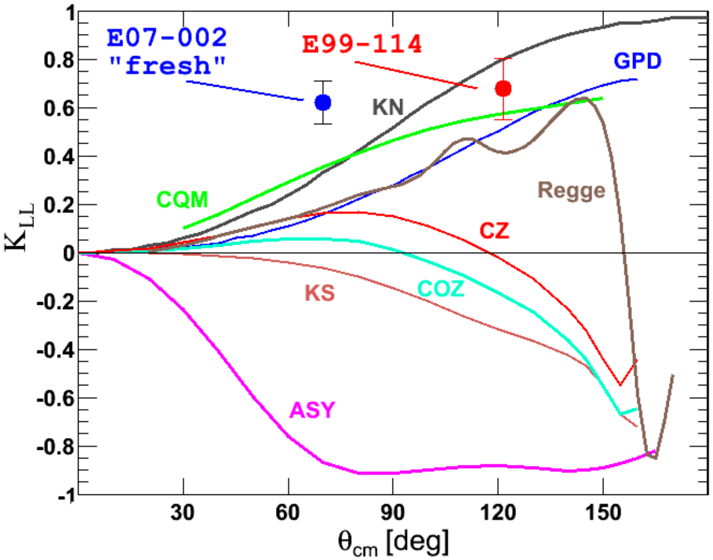
- Ongoing work: quantify impact of measurement on GPD extractions

Magnet-Dump as a Compact Photon Source

- Idea was discussed at the November 2014 NPS collaboration meeting
  - Uses a magnet as dump for the electron beam producing a narrow intense untagged photon beam
  - Could provide the means to carry out real-photon type experiments with vertically bent spectrometers



E99-114: $s = 6.9,\ t = -4.0,\ u = -1.1$
E07-002: $s = 7.8,\ t = -2.0,\ u = -4.0$



- **PR12-15-003:** worked out the concept in more detail for WACS-ALL measurements with NPS extending the range in s with wide kinematic coverage

PAC43 report: "The PAC was impressed by the concept for a new photon source. It strongly encourages the proponents to work with the members of the previously approved E12-14-006 to see whether it could be included there"

NPS General Design Concept

- a ~25 msr neutral particle detector consisting of up to 1116 **$PbWO_4$ crystals** in a temperature-controlled frame including gain monitoring and curing systems

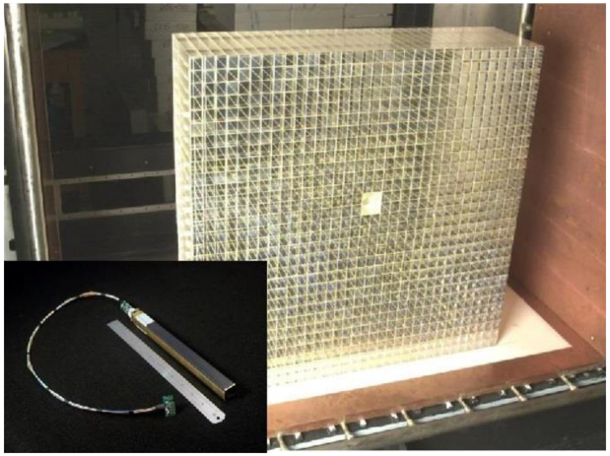
- HV distribution bases with built-in amplifiers for operation in a high-rate environment

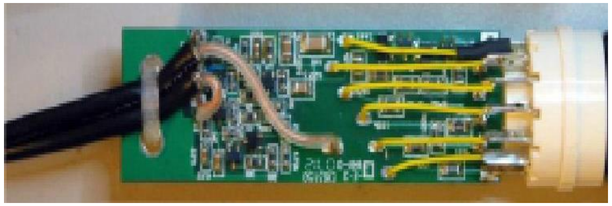
- Essentially deadtime-less digitizing electronics to independently sample the entire pulse form for each crystal – JLab-developed Flash ADCs

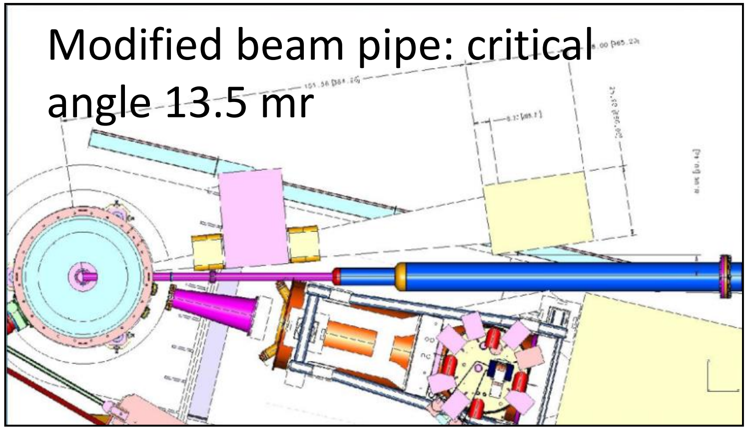
- A new sweeping magnet allowing for small-angle operation at 0.3 Tm (for electro-production) and large angle operation at 0.6 TM (for photo-production). The magnet is compatible with existing JLab power supplies.

- 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 - Synergies with other JLab Projects

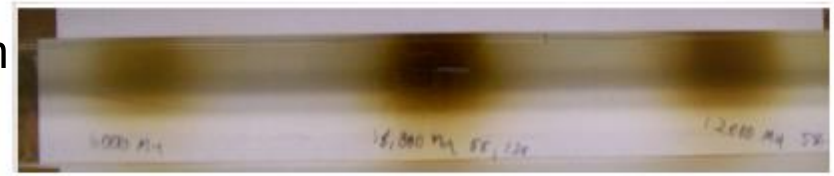
- Hall D considering to construct a radiation hard insert for the forward calorimeter
  - Expected dose (center): 100kRad/10Y at “high intensity” (100MHz in coherent peak)

- FCAL insert requirements:
  - Good resolution in energy and position
  - Good radiation hardness in center

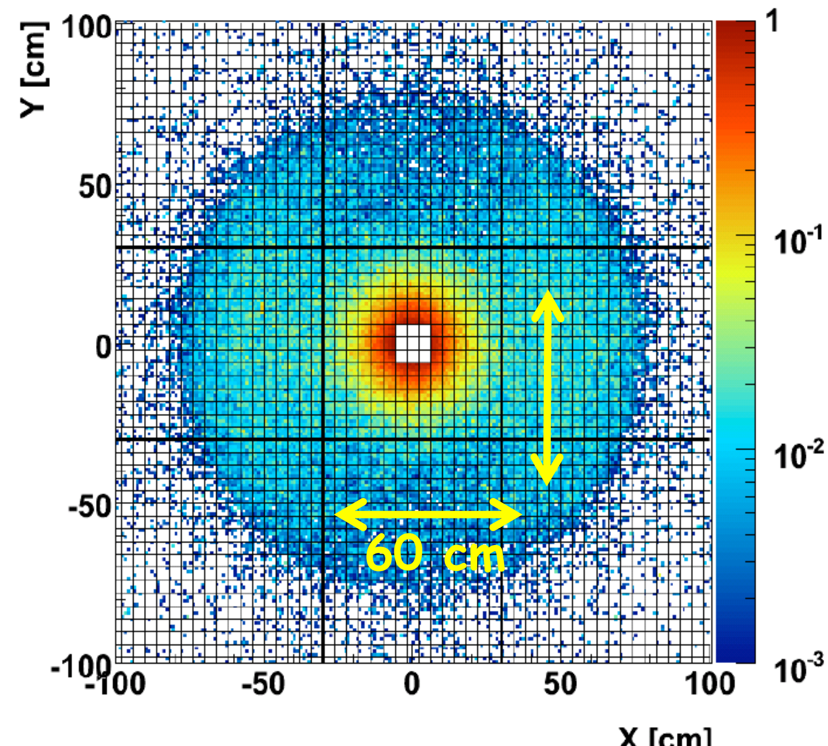
- PbWO4 would be optimal due to its small Moliere radius and radiation hardness

NPS crystal quality studies will play an important role in crystal selection

Measurements using 20 MeV e⁻

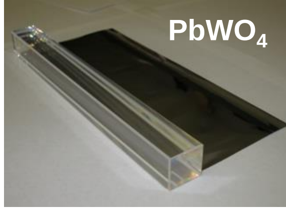


300 kRad 700 kRad 500 kRad



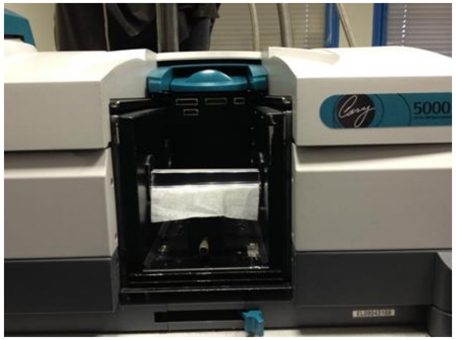
Calculations, in kRad/Year at “low intensity”

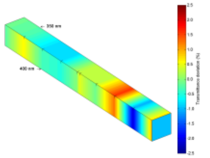
NPS Project Status

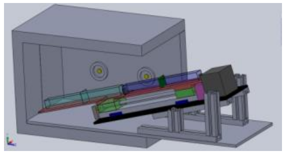


- 2015 NSF/MRI funding proposal was selected for an award
  - Award will provide for NPS infrastructure, including the magnet, assuming existing crystals
  - In the ideal case the NPS would use new crystals
  - Application for UK grant with emphasis on additional equipment aimed at WACS requirements submitted

- Significant efforts of the NPS collaboration have recently been related to $PbWO_4$ crystals
  - 10+5 PbWO4 crystals produced by SICCAS have been tested for optical properties and radiation hardness; 30 more crystals on order
  - Infrastructure for crystal testing being developed at IPN-Orsay and CUA
  - Close collaboration with Giessen University on crystal evaluation, as well as Caltech and BNL





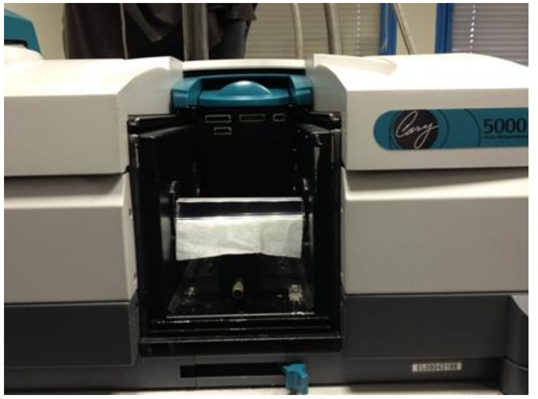


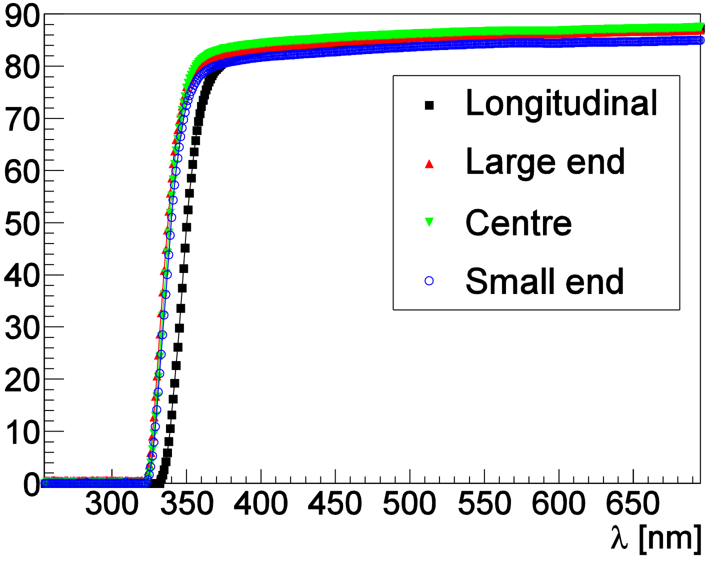
More info in the NPS Wiki: https://wiki.jlab.org/cuawiki/index.php/Main_Page

Crystal testing at universities

IPN-Orsay group: Gabriel Charles, Giulia Hull, Carlos Munoz-Camacho

- Optical Transmittance Measurements
  - Varian Cary 5000 spectrometer
    - Measures absorption along and across the crystal with 1nm wavelength resolution between 200 and 800 nm
  - Setup was commissioned with BTCP crystals on loan from University of Giessen
  - To accommodate crystals of lengths greater than 15 cm a more versatile configuration with a fiber-based spectrometer is being built
- Crystal light yield
  - A setup is currently being tested with cosmic rays
- Options for crystal irradiation are being explored



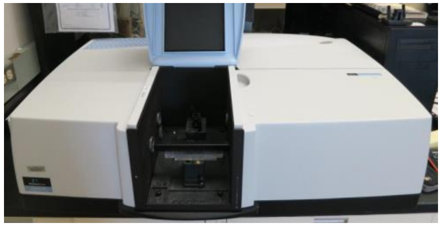


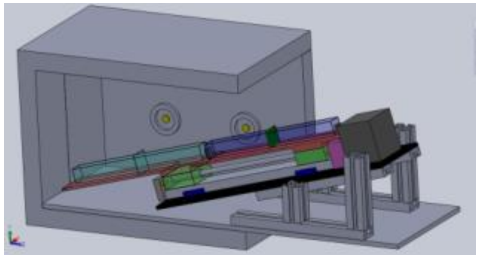
Crystal testing at universities

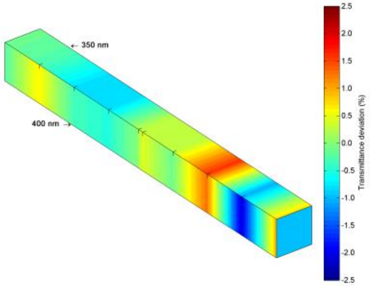
THE CATHOLIC UNIVERSITY *of* AMERICA

CUA group: Marco Carmignotto, Indra Sapkota, Arthur Mkrtchyan, Tanja Horn

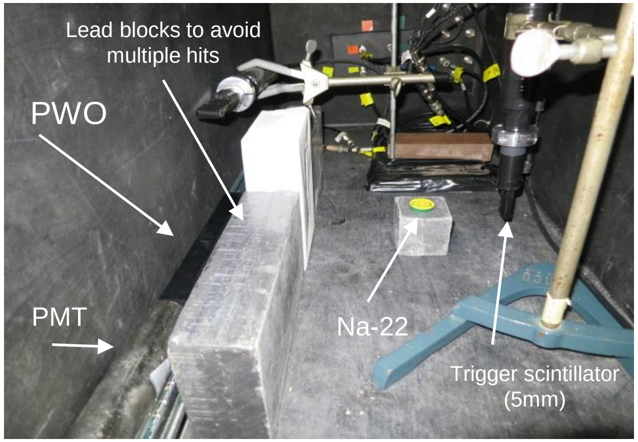
- Optical Transmittance Measurements
  - Perkin-Elmer Lambda 750 spectrometer
  - Setup was commissioned with BTCP crystals on loan from University of Giessen – reproducibility ~0.2%
  - To accommodate lateral measurements of crystals of lengths greater than 15 cm a stepper motor XSlide assembly will be used

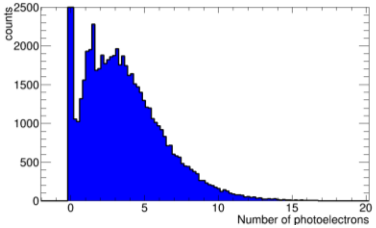


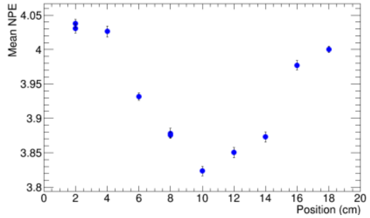




- Crystal light yield
  - A setup consists of a Na-22 source and calibrated PMT

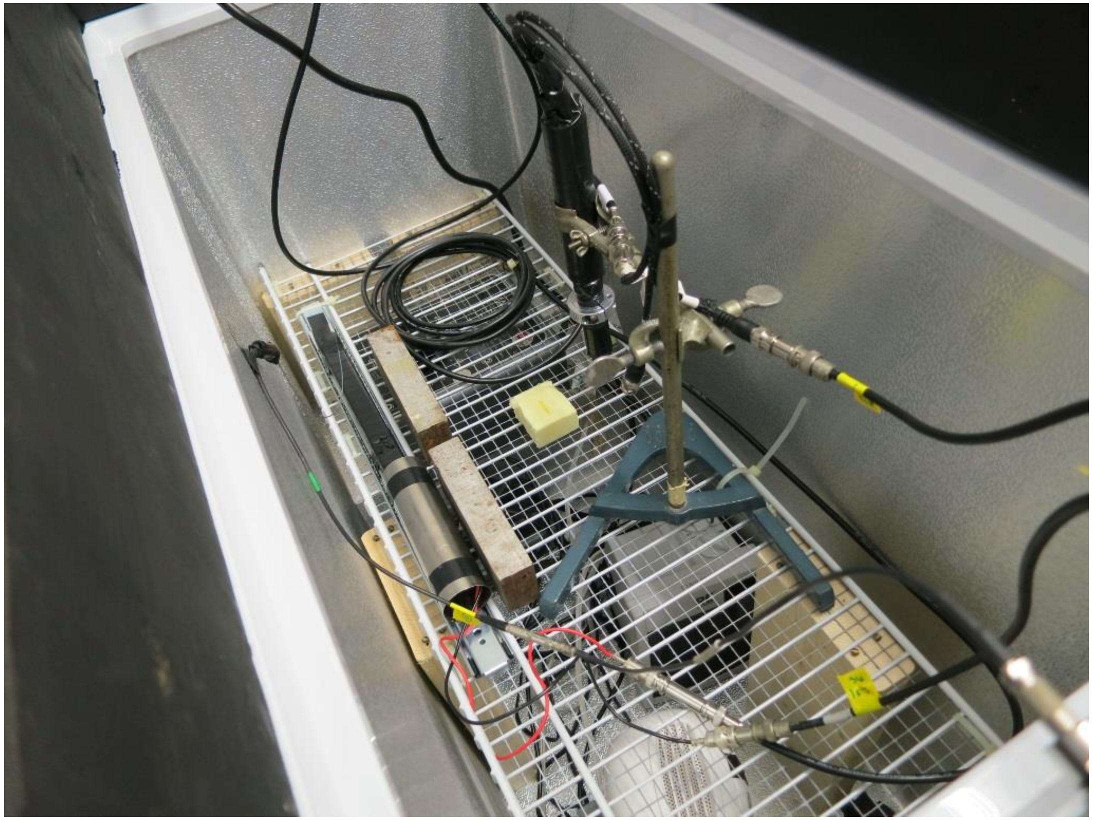




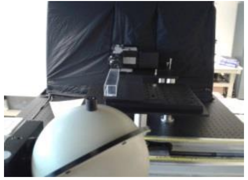


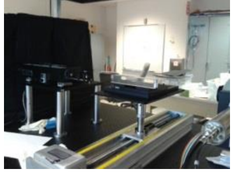
Crystal testing at universities

- Temperature stabilization options



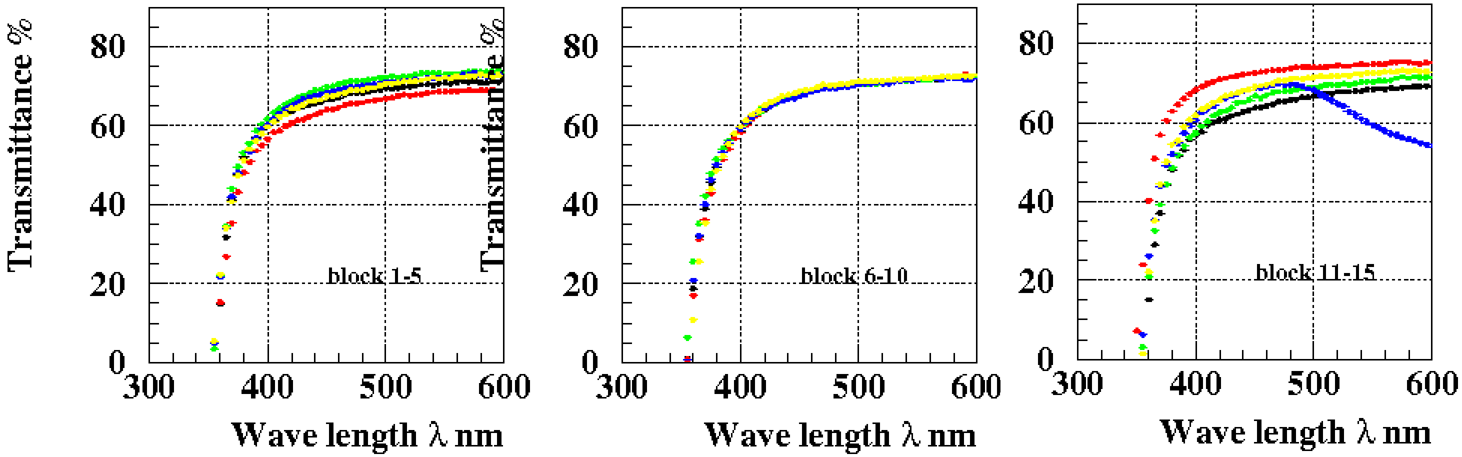
Optical Properties of 2014 produced SIC PWO crystals





- Optical properties of 10+5 PWO crystals produced by SIC in 2014 (spring and December) were tested for optical properties at JLab
  - Halogen lamp, integrating sphere, holder table for crystal, optics
  - Reproducibility ~few percent – main uncertainty is crystal orientation

Longitudinal Transmittance

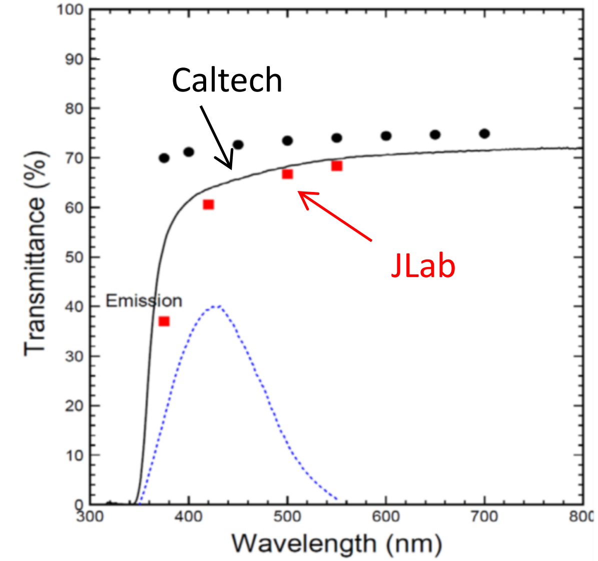


- Crystals are of better quality than previous ones
- Still need to determine crystal homogeneity

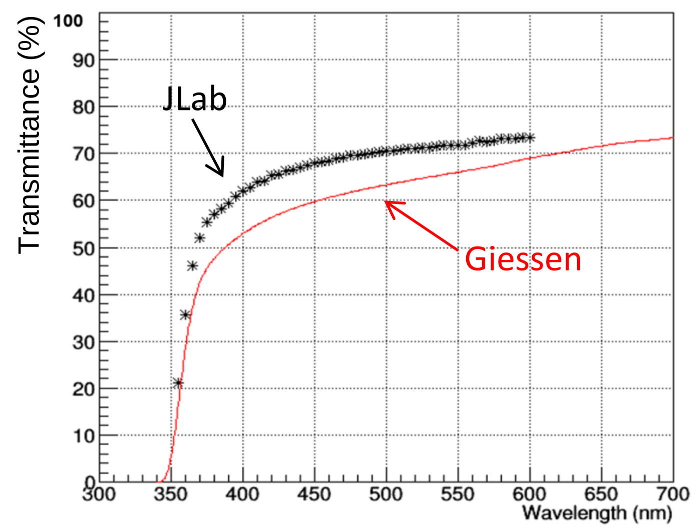
Arshak Asaturyan, Hamlet Mkrtchyan (Yerevan), A. Mkrtchyan (CUA)

Understanding systematic effects

- Subsets of crystals were tested at different facilities:
  - Crystals #5 and #11 at Caltech
  - Crystals #7 and #15 at BNL
  - Crystals #2, 3, 6, 8, and 9 at Giessen University



- Preliminary results suggest that the values of the transmittance measured at:
  - Caltech are *higher* than those measured at JLab
  - Giessen and BNL are *lower* than those measured at JLab
    - On average the values are lower by 10-15% though for crystal #2 the difference is more than three times as much



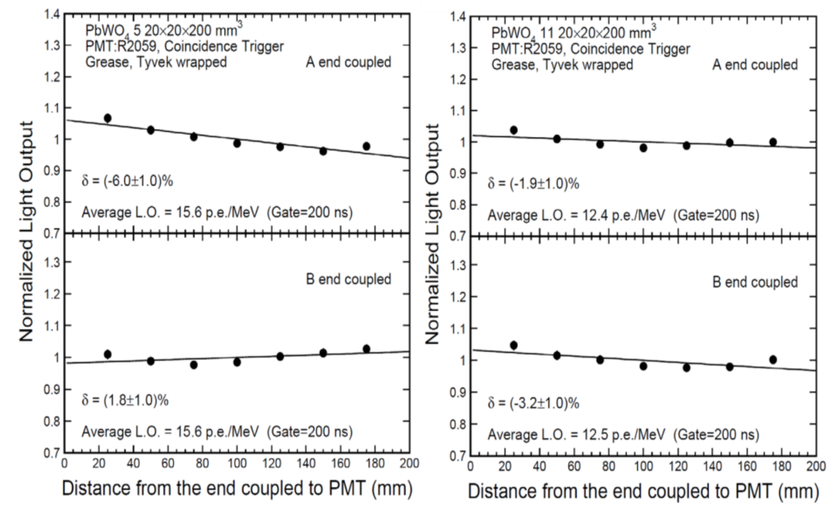
Setup dependent systematic effects under study

Caltech: R-Y Zhu, Giessen: R. Novotny, V. Dormenev

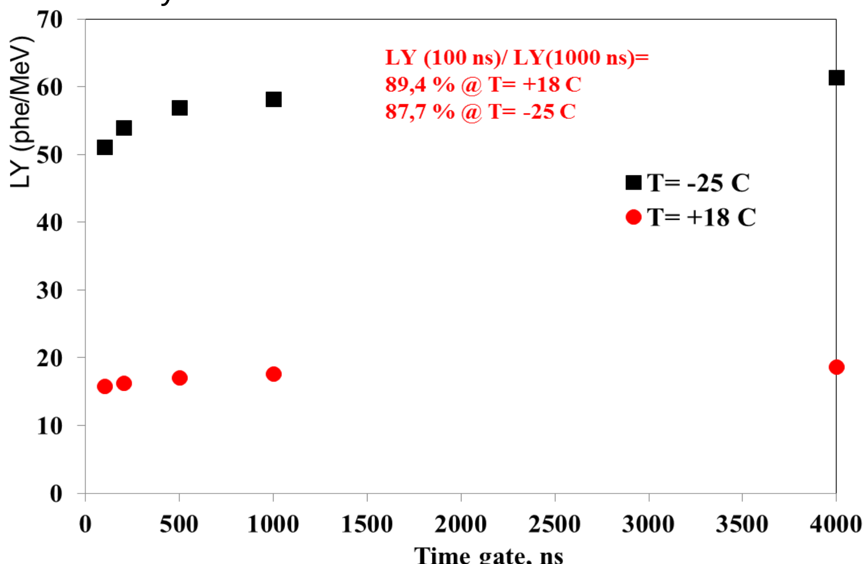
Light Yield of 2014 produced SIC PWO crystals

- Initial measurements of subsets of crystals show:
  - LY response of 15-16 p.e./MeV though some crystals have a lower yield
  - LY increases by a factor of ~3 due to cooling to -25 ˚C independent of integration gate

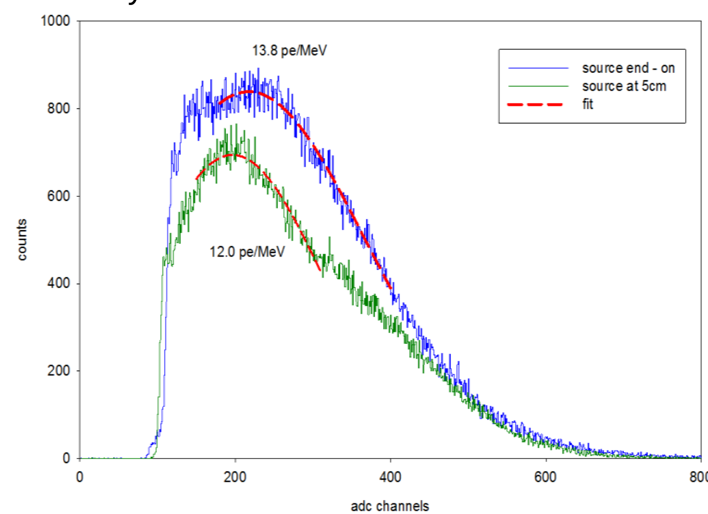
Crystals #5 and #11 measured at Caltech



Crystal #2 measured at Giessen Univ.



Crystals #7 and #15 measured at BNL

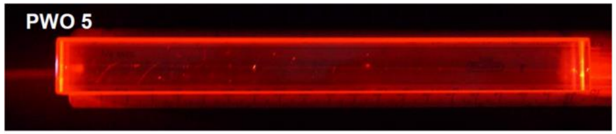


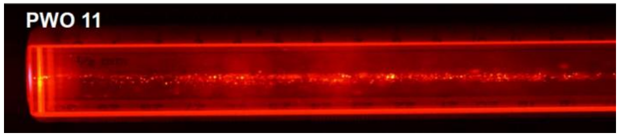
BNL: C. Woody, S. Stoll, Caltech: R-Y Zhu, Giessen: R. Novotny, V. Dormenev

Comparison with CMS crystals

- Subset of crystal samples is consistent with CMS quality standards
  - Crystal #5 transmittance is better and #11 is worse than the average of CMS crystals

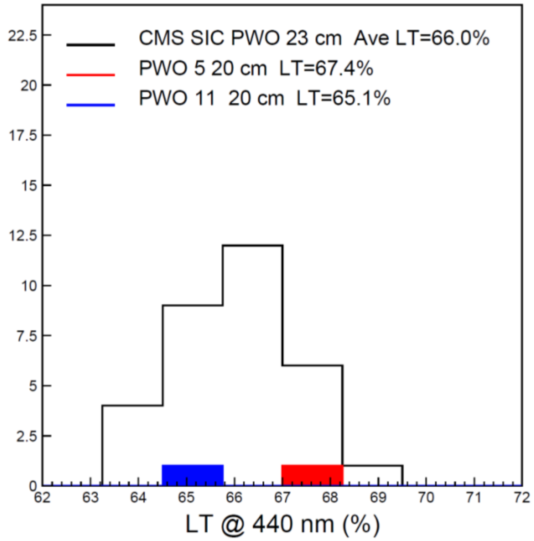
    [IEEE Trans.Nucl. Sci. NS-51 1777]



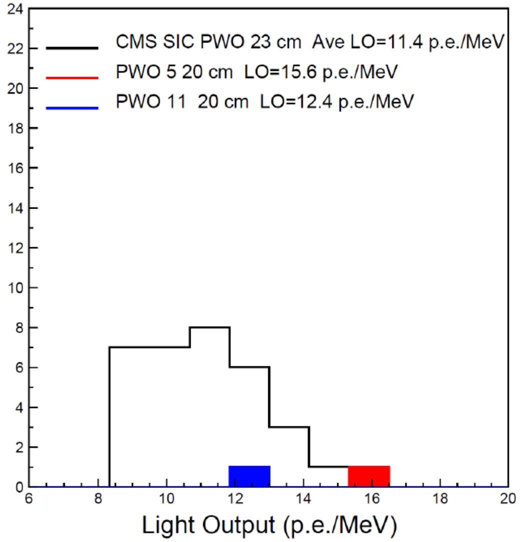


- Initial measurements show higher light output and faster decay time of both samples compared to CMS quality standards

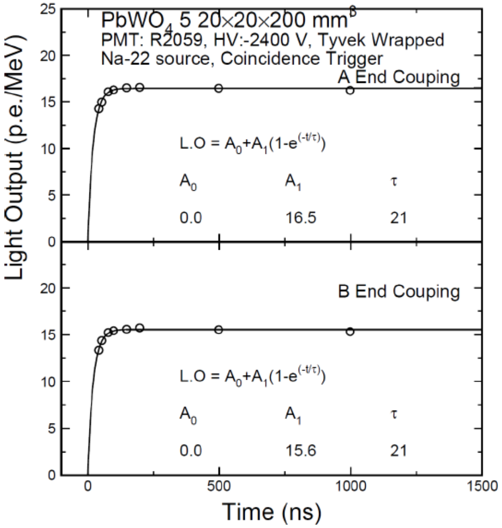
Longitudinal Transmittance (LT)



Light Yield

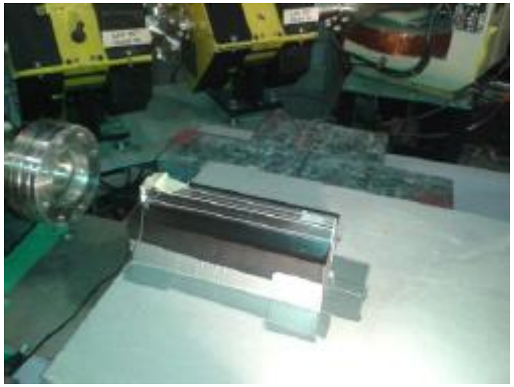


Decay Kinetics



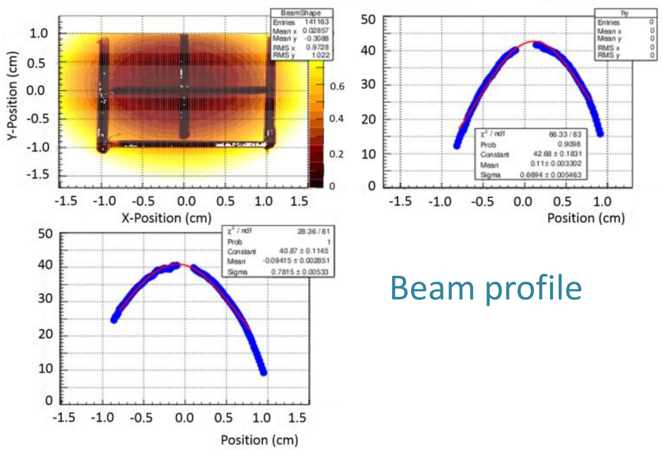
Crystal irradiation with beam to study radiation damage effects

- Tests carried out with electron beam at the Idaho Accelerator Facility
  - 20 MeV electrons, 0.1 Hz repetition rate, I_{peak}=111 mA (per pulse) and 100 ns pulse width
  - Radiation dose rate: ~13 krad/hr

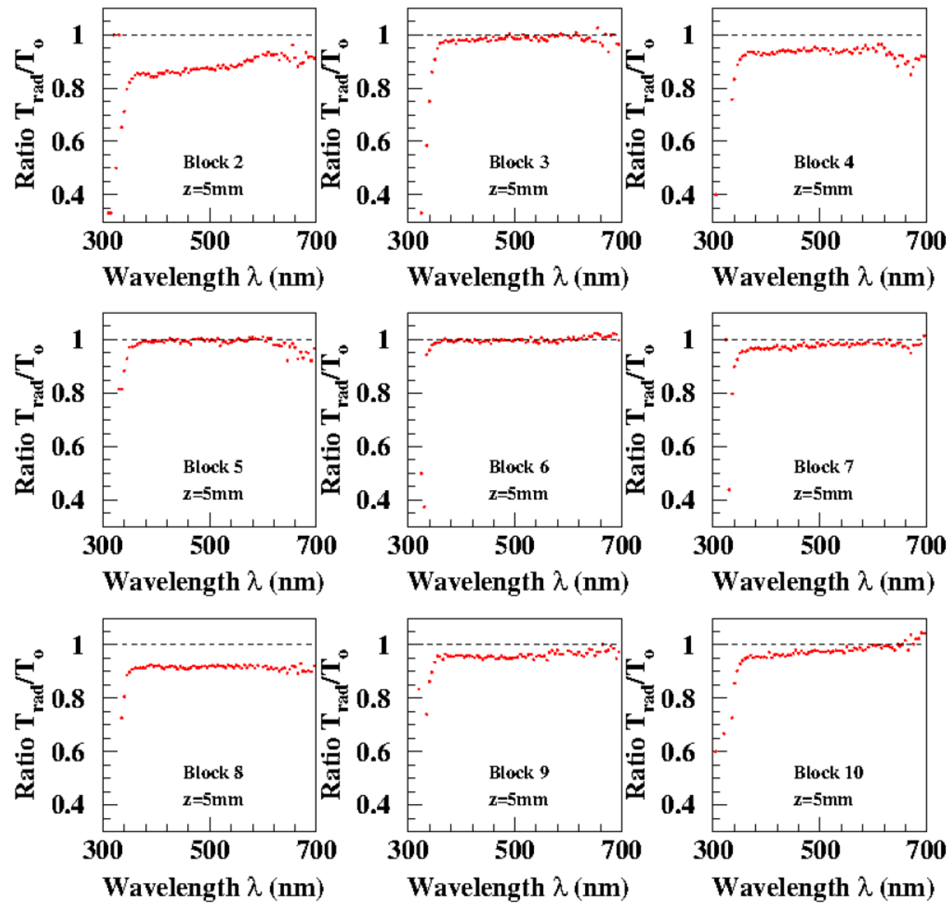



Arshak Asaturyan, Hamlet Mkrtchyan (Yerevan), Carlos Munoz-Camacho (IPN-Orsay), Hashir Rashad (ODU)

Radiation Damage Effects



Beam profile

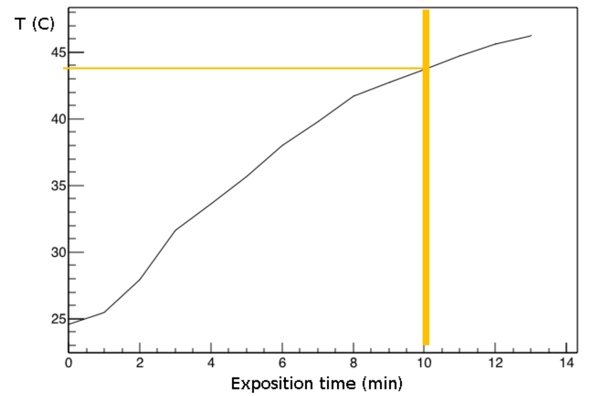


- Transmittance of some crystals changed more than 15% after an accumulated dose of 432 krad (at a dose rate of 1.3 Mrad/hr)
- Effect of radiation damage is in part spontaneously recovered after a time period of 60 hrs

Preliminary tests of radiation hardness show high resistance of the crystals to the doses expected for the approved NPS experiments

Challenges of radiation damage tests with beam

- **Temperature uniformity** during exposure difficult to control with electron beam
  - For irradiation at dose rate 1.3 Mrad/hr for 20 min exposure the temperature near the crystal front increased from 23-25˚C to 36-37˚C
  - For similar exposure time at dose rate 2.6 MRad/hr the temperature increases from 24˚C to 46˚C resulting in crystal damage



  - To reach higher doses crystals need to be cooled down between exposures to avoid thermal damage

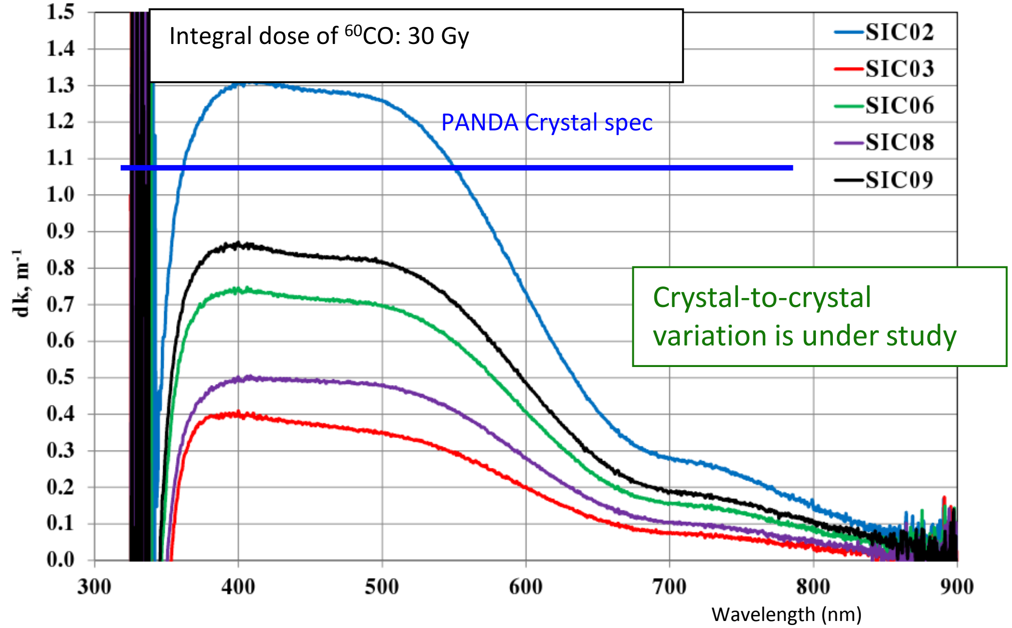
- ***Spontaneous recovery** of components with fast relaxation time*
  - To minimize this effect all transmittance measurements were carried out 10 minutes after irradiation

- ***Surface effects***

Tests at lower dose rates and uniform dose distributions would allow for better understanding radiation damage effects

Preliminary studies of radiation damage effects with sources

- A subset of crystals was irradiated at Giessen University
  - Integral dose of 30 Gy imposed within an irradiation period of about 15 minutes.
  - The crystals are kept light tight during and after irradiation
  - Transmittance measurement performed exactly 30 minutes after the end of the irradiation.



- The impact of radiation effects is quantified in terms of the change in the absorption coefficient

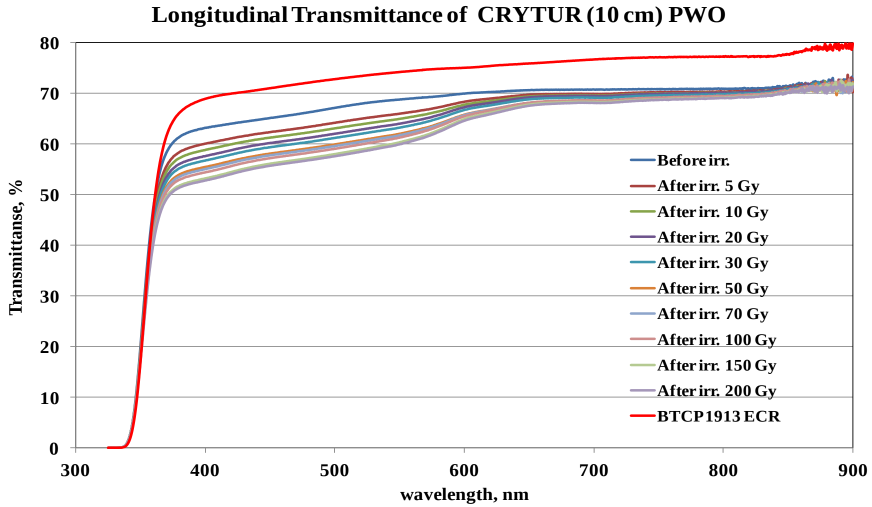
$$dk = \ln\left(\frac{T_0}{T_{rad}}\right) \cdot d^{-1}$$

Preliminary results from irradiation with beam in Idaho and *initial tests* of a subset of crystals in Giessen suggest that crystals have high radiation resistance

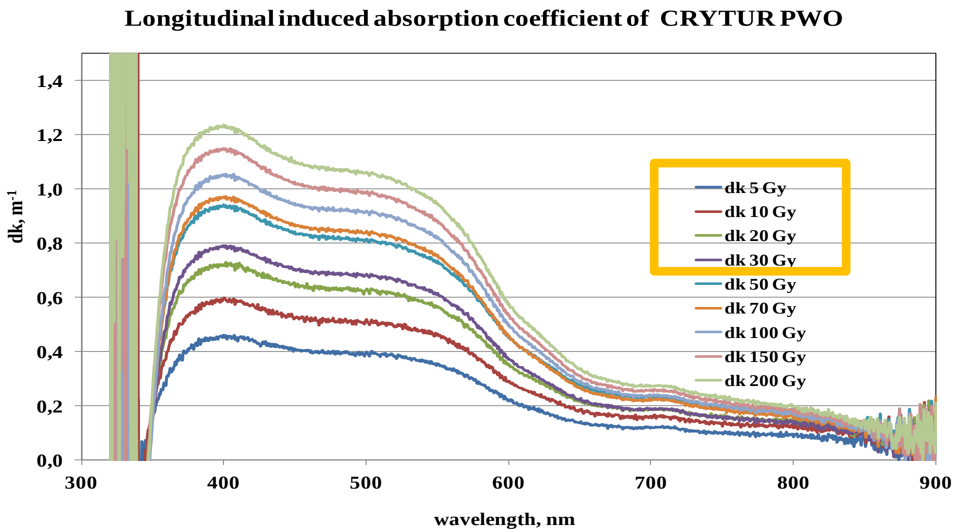
- Further tests to better understand radiation damage effects underway

Status of CRYTUR Crystal Production

- First full-size crystal produced with size 2x2x20cm^3
  - Produced using raw material from BTCP
  - Some longitudinal inhomogeneity



- Results of optical and radiation hardness studies suggest that:
  - Transmittance falls within 8% of the BTCP crystals at 420 nm
  - Crystals have sufficient light yield
  - Crystals are radiation hard for dose rates go up to 100 Gy (spec: 30 Gy)

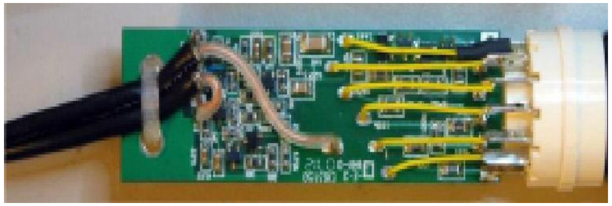


Evaluation of the first full-size crystals produced by alternate manufacturer CRYTUR also indicates the potential for high quality crystal production

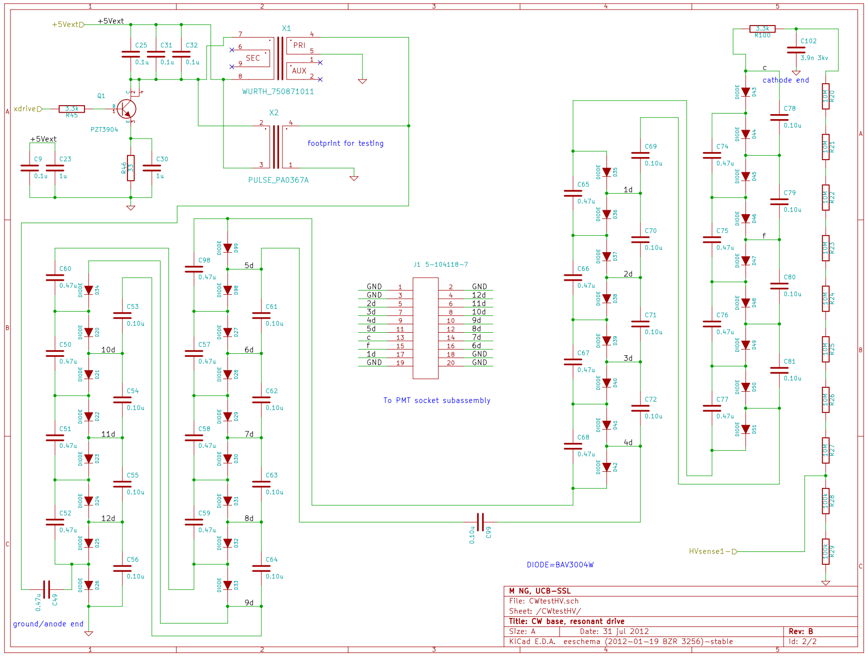
PMT HV bases

- NPS default solution: resistive bases with transistor stabilization
  - Have been designed and tested

    [V. Popov, H. Mkrtchyan, NSS/MIC, 2012 IEEE]



- Studying relative benefits of Cockcroft-Walton DC transformer base at ODU
  - Design from BNL ANDY and Jlab Radphi experiments
    - No HV cabling required
    - Lower current draw, lower power
  - Dynodes feed from Cockcroft-Walton stages. No resistive divider.
  - Stabilization via digital feedback (not shown)



ANDY base design

Summary and Outlook

- NPS science program: 5 approved experiments to date
  - Additional experiment ideas
  - Interesting new development: photon source

- NPS 2015 MRI was selected for an award

- NPS crystal testing activities are beneficial for PWO-based calorimetry world-wide - other JLab projects
  - Planning to test additional 30 SIC 2015 crystals in next few months

- NPS near term activities
  - Detailed design drawings for the NPS frame and the sweeping magnet
  - Procurement of some bases and amplifiers and assembly
  - Procurement of some of the magnet materials