R&D for high resolution calorimetry at the future Electron-ion collider

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Carlos Muñoz Camacho
(for the eRD1 calorimetry consortium)

Institut de Physique Nucléaire d'Orsay,
CNRS/IN2P3 (France)

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Unité mixte de recherche
CNRS-IN2P3
Université Paris-Sud

91406 Orsay cedex
Tél. : +33 1 69 15 73 40
Fax : +33 1 69 15 64 70
http://ipnweb.in2p3.fr

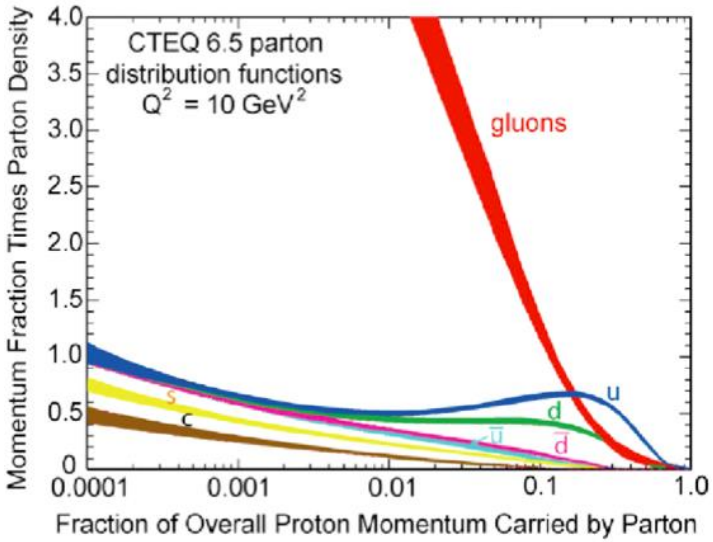
munoz@ipno.in2p3.fr

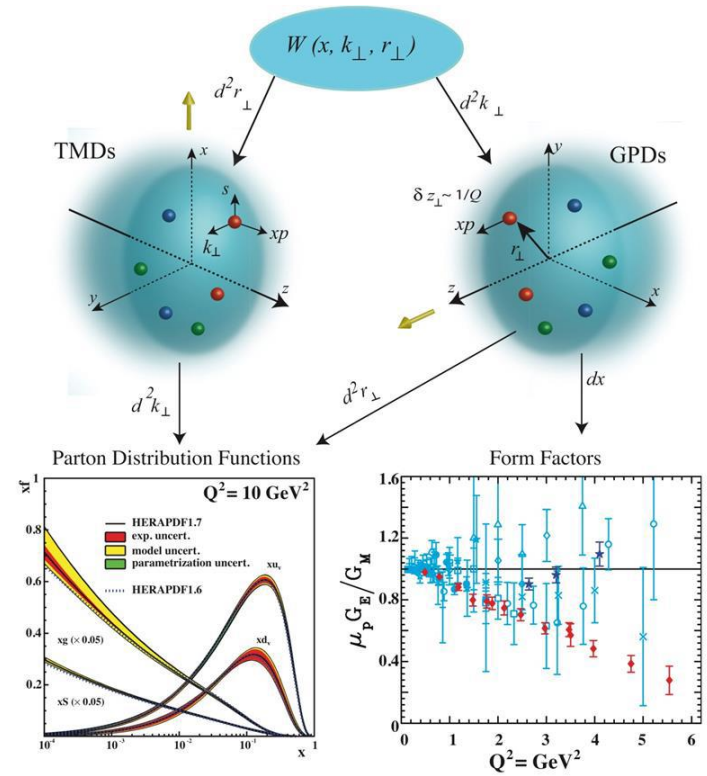
Electron-Ion Collider: physics highlights

3D structure of the nucleon is nontrivial

- Far more than the simple valence quark structure
- How proton properties arise from the elementary constituents?

How do gluons confine themselves into hadrons





Gluon dynamics plays a large role in proton spin

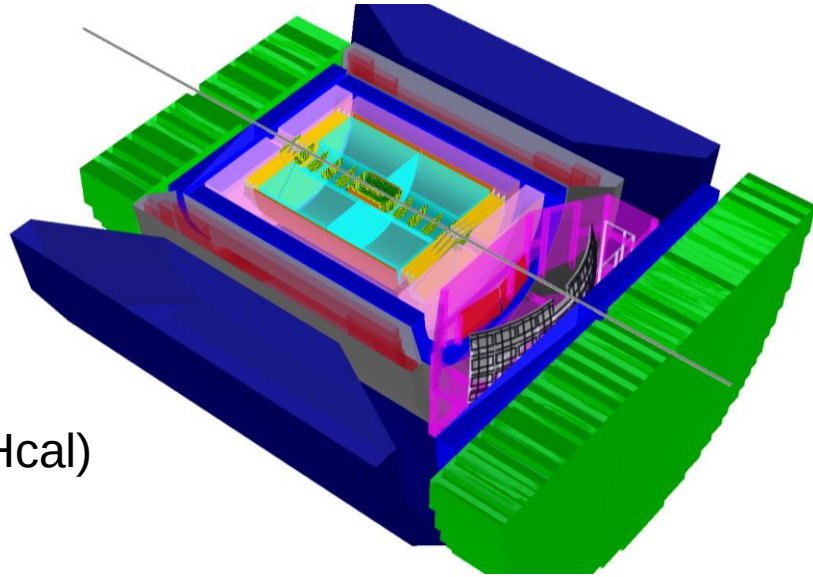
- Spin=intrinsic (parton spin) + motion (orbital angular momentum)

Dynamical balance between gluon radiation and recombination

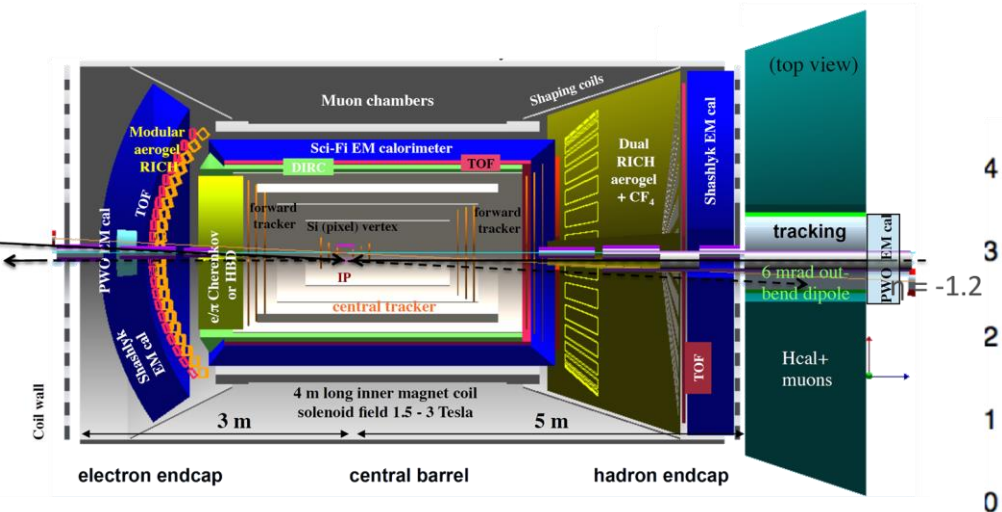
Saturation of gluons?

Calorimetry for EIC

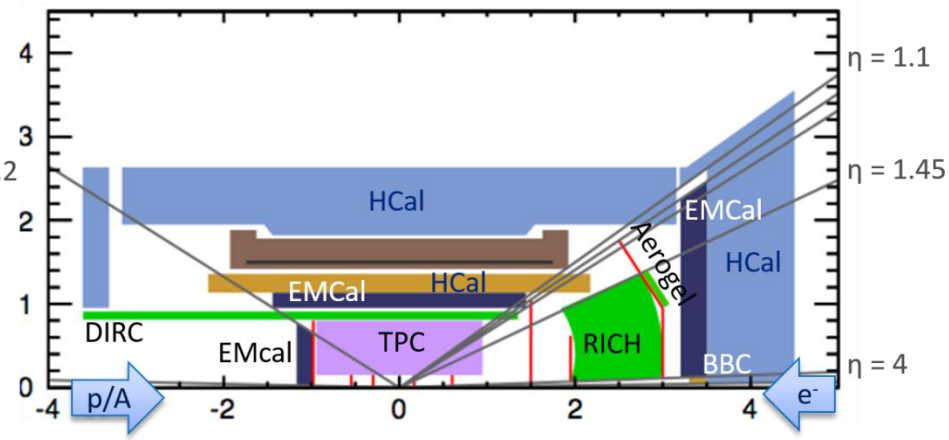
- Electron identification and triggering (e-EMC, barrel EMC)
- Electron kinematic measurements (e-EMC, barrel EMC), high resolution needed.
- Jet, DIS kinematics and triggering via hadron final states (barrel EMC/Hcal, h-EMC/Hcal)
- Photon ID for DVCS
- Diffractive ID via rapidity gap (h-HCal)
- High momentum track energy measurement (h-Hcal)



BeAST (Brookhaven eA Solenoidal Tracker)



Jlab EIC detector design



Babar-magnet based detector (RHIC)

Ongoing calorimetry R&D for EIC

Consortium created in 2012, funded by generic EIC detector R&D funds from US DOE

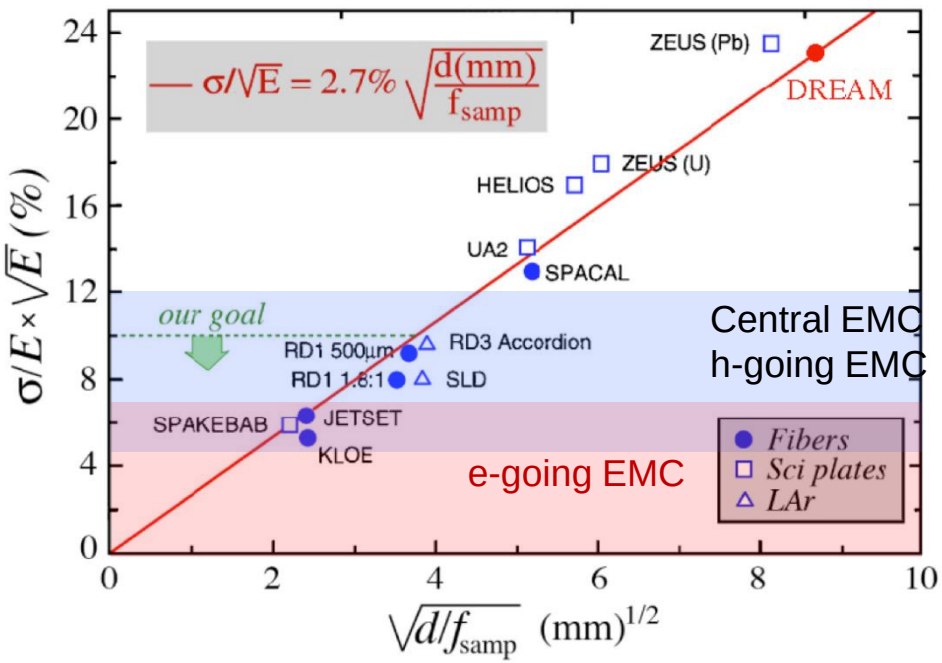
- Sci-fiber EM calorimeter (SPACAL)
  Compact W-scifi calorimeter, developed at UCLA
  Investigating high resolution version for e-going endcap
  Investigating large scale production and projectivity, driven by sPHENIX project
- Crystal EMCal at small angle: high energy resolution and PID needed
  Option for high resolution e-going endcap calorimeter
- Shashlyk EMCal
  Option for h-going endcap calorimeter
- HCal
  Prototype development in collaboration with STAR forward upgrade and sPHENIX
- Sensor
  SiPM and APDs, radiation studies and support electronics
- Simulation
  Full detector simulation and analysis frameworks

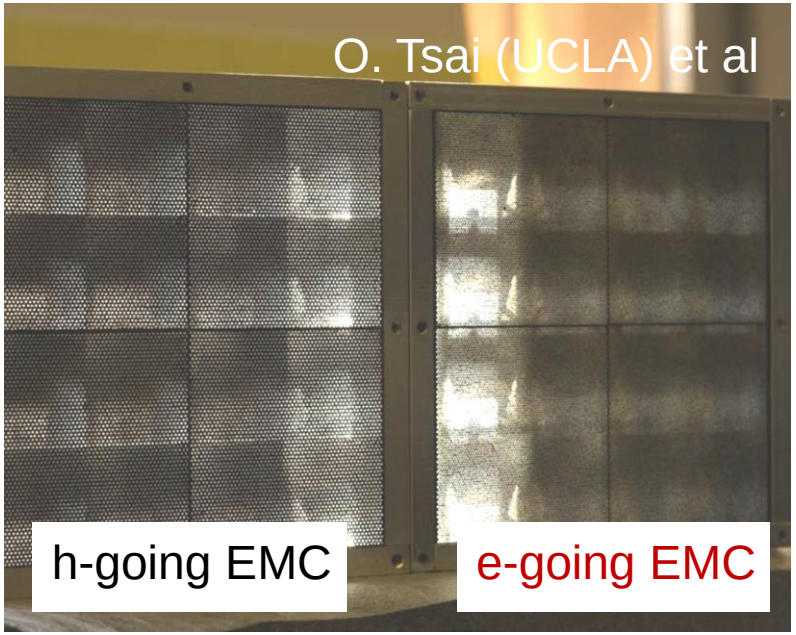
SPACAL: towards high energy resolution

- For e-going endcap ECal, high resolution is preferred:
  With the SPACAL technology, higher resolution could be achieved with high sampling frequency and fraction

- UCLA tested W(75%)/Sb(25%) – SciFi SPACAL with d=0.67mm in 2015, but the light yield is low w.r.t. expectation.

- Study on high resolution SPACAL test beam last week!





SPACAL beam test at FermiLab (May 4-10, 2016)

Goals:

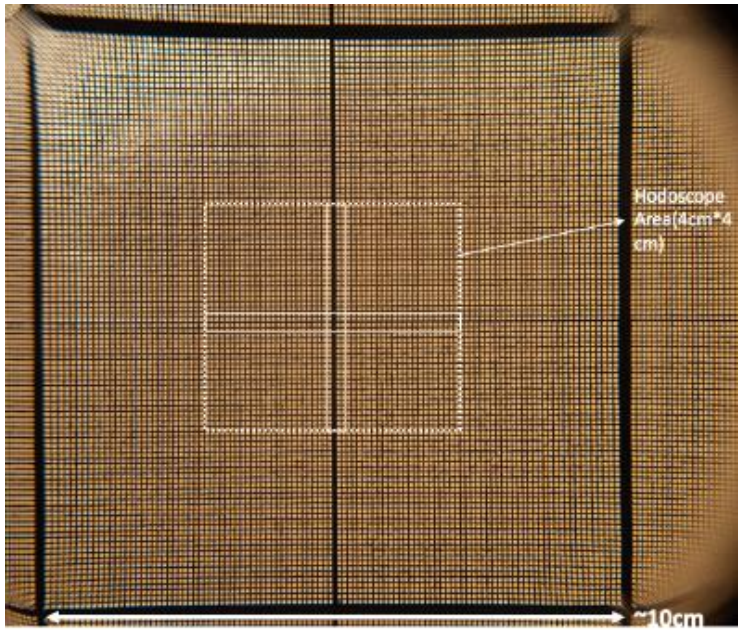
- Is production homogentity of the block sufficient?

(SF kept within +-0.2% from block to block during production)

- Is local density/composition variations are under control?
- (W/Sn composite absorber during packing)
- Is light yield is sufficient to think about compact readout with Si sensors in future?
- What is the effect of 'dead' area between superblocks.

What are benefits of using square fibers?

Two prototypes:
a) High Frequency.
b) High Sampling Fraction

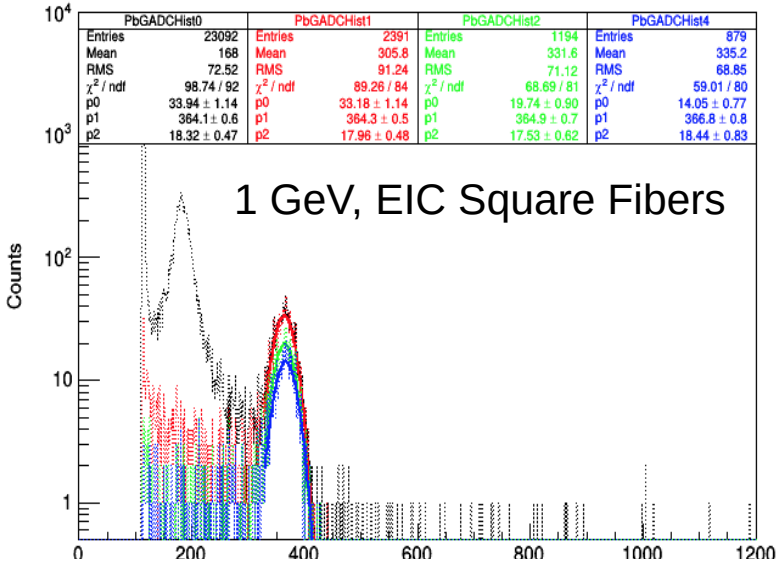


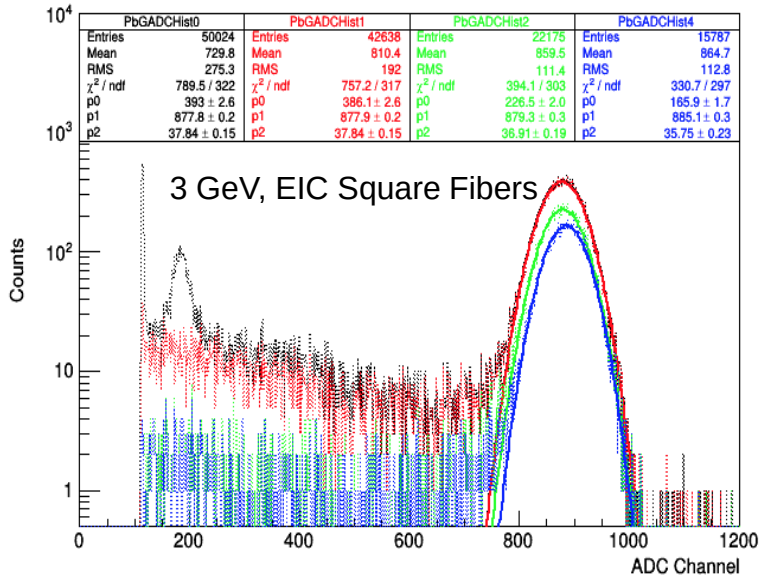
Results presented for the worst case scenario:

- Impact hits selected with sc. Hodoscope centered between four blocks
- Impact angle 10 deg (minimal angle for EIC)
- Energy scans taken with orientation of 'wide' central gap being vertical as shown and horizontal, i.e. for cases when narrow core of EM showers sample or integrate dead area.

O. Tsai

SPACAL beam test: results

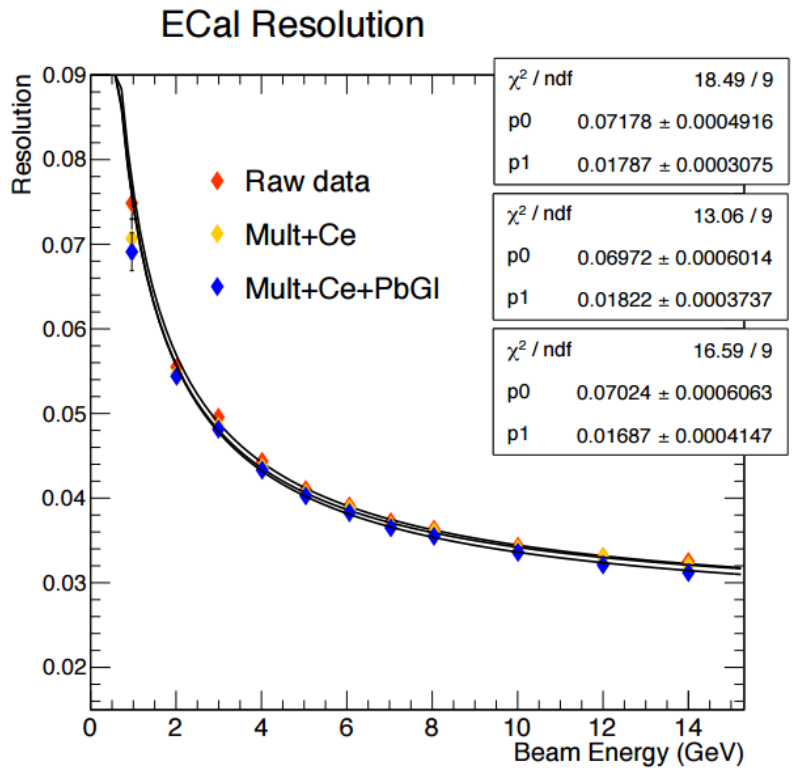




Beam energy spread ~2%

Square fibers meet EIC design goals

$$f(E) = \sqrt{\frac{p_0^2}{E} + p_1^2 + 0.01875^2}$$



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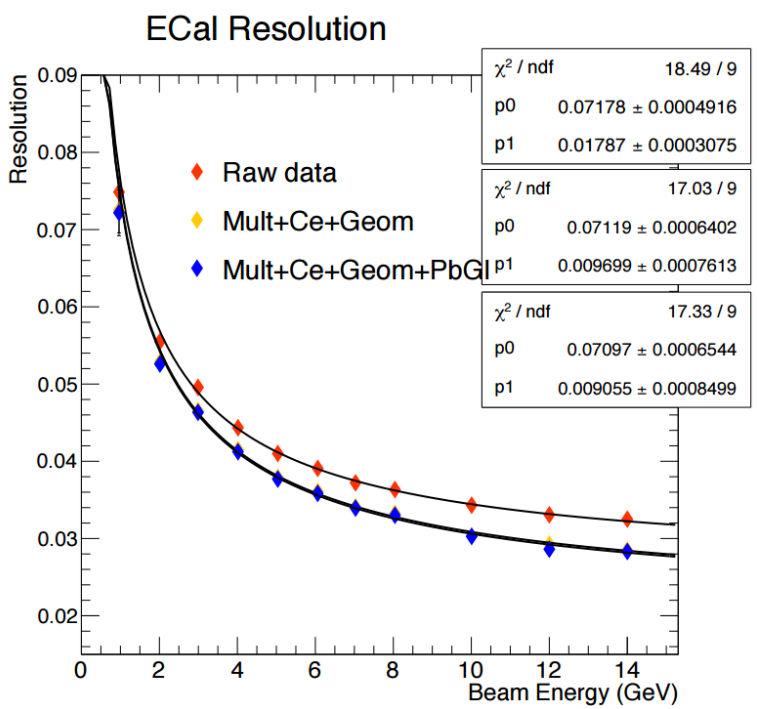
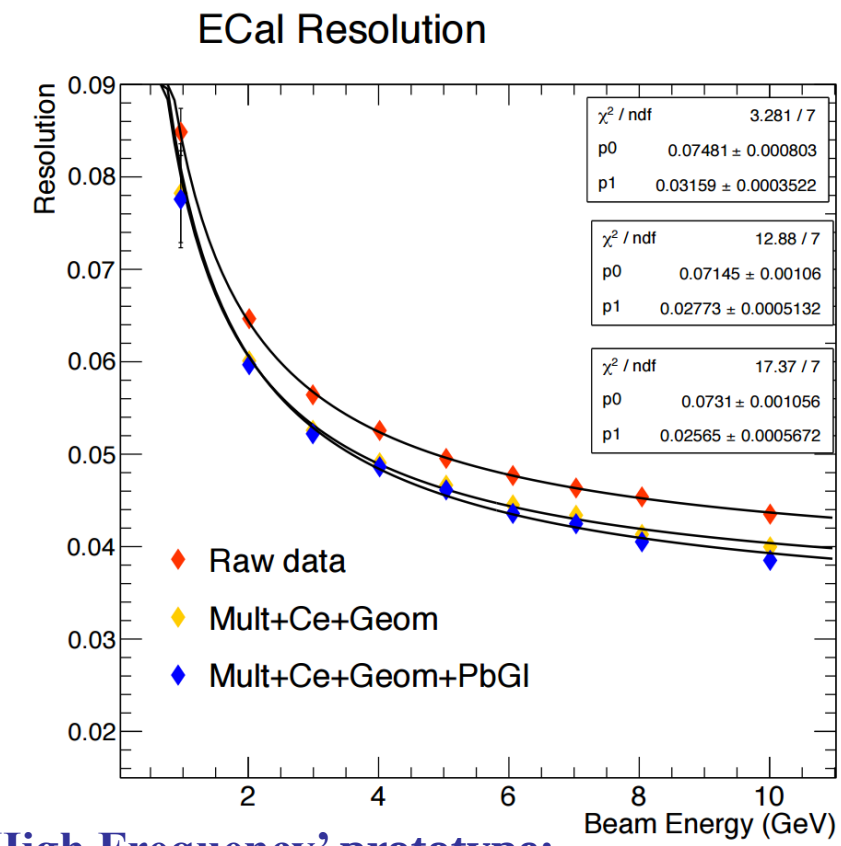
SPACAL beam test: results

Effets of cracks in E resolution



Constant term < 1%, when
removing hits +/- 2.5 mm near the cracks.

W/Sn composite absorber and thin fibers



'High Frequency' prototype:

Combination of composite absorber and thin fibers leads to internal in homogeneities, which increases constant term about factor of three (3%) compare to detector build from square fibers.

O. Tsai

SPACAL beam test: conclusions

- Is production homogentity of the block sufficient?

Yes, for Square Fiber EM Prototype.

- Is local density/composition variations are under control?

Probably No, for composite absorber.

- Is light yield is sufficient to think about compact readout with Si sensors in future?

Yes, 5000 p.e./ GeV, Square fibers.

- What is the effect of 'dead' area between superblocks.

Increased constant term, need to reduce 'vertical' crack in future.

- What are benefits of using square fibers?

More light, shape may be more suitable for future compact readout.

Very promising results, already better than excellent H1 EMcal. Clear direction for future developments and improvements.

High resolution calorimetry for electron endcap

PID requirements in the electron endcap primarily driven by semi-inclusive and exclusive processes, e.g., DVCS
Detection at very small angle is needed

EM calorimetry has two main functions:

- **particle identification**: important for discriminating single photons from, e.g., DVCS and two photons from p0 decay, and e/p.
- **particle reconstruction**: driven by the need to accurately reconstruct the four-momentum of scattered electrons at small angles, where the angular information is provided by the tracker, but the momentum (or energy) can come from either the tracker or the EM calorimeter.

Requirements:

- Good resolution in angle to at least 1 degree to distinguish between clusters
- Energy resolution to a few %/sqrt(E) for measurements of cluster energy
- Ability to withstand radiation down to at least 1 degree with respect to the beam line

Collaboration: BNL, Caltech, CUA, IPN-Orsay

PWO crystal specifications

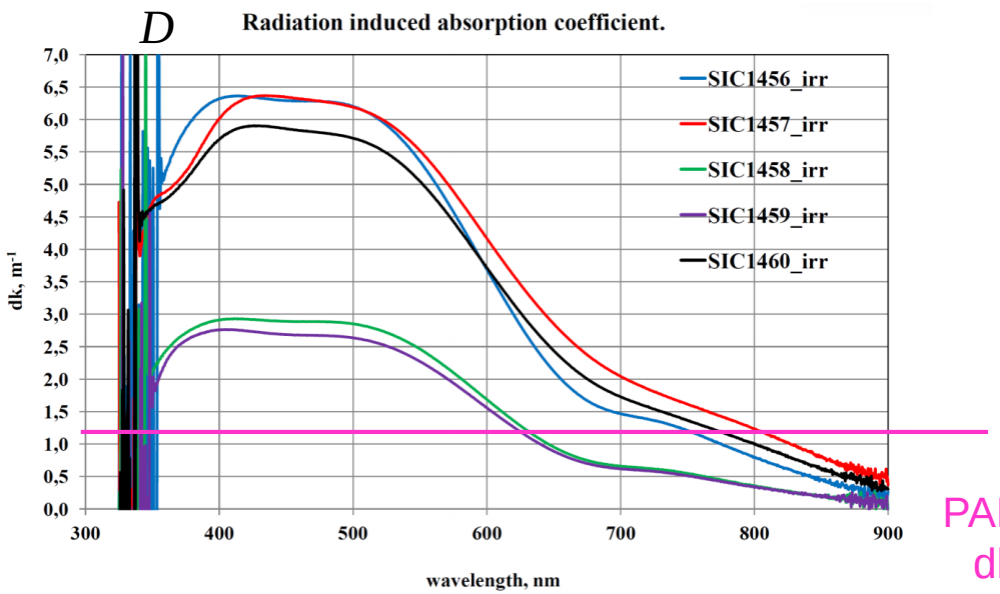
Parameter	*Unit*	*CMS PWO-I*	*PANDA PWO-II*	*EIC*
Luminescence maximum	nm	420	420	420
Expected energy range of EMC	GeV	0.15-1000	0.01-10	0.1-15
Light Yield at RT	phe/MeV	8.0	16.0	15?
EMC operating temperature	°C	+18	-25	
Energy resolution at 1 GeV	%	3.4	2.0	few %/√E
LY(100ns)/LY(1us)		0.9	0.9	
Optical 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	

A key question of ongoing R&D is to determine whether the EIC could use more relaxed crystal specs, also in terms of parameter variation between crystals

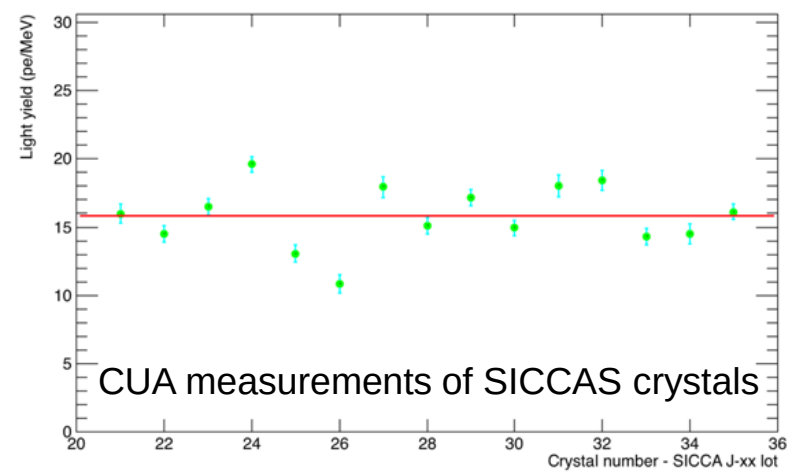
High resolution calorimetry based on $PbWO_4$ crystals

- $PbWO_4$ has been extensively used for high precision calorimetry (CMS, JLab, PANDA…) because 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, but has problems maintaining good crystal quality.
- Need to develop an alternate supplier of $PbWO_4$ in order to ensure worldwide availability of high quality crystals (potential candidate: CRYTUR, Czech Republic).

$$dk = \frac{\ln(T_{bef} / T_{aft})}{D}$$



Light yield: large variations crystal to crystal



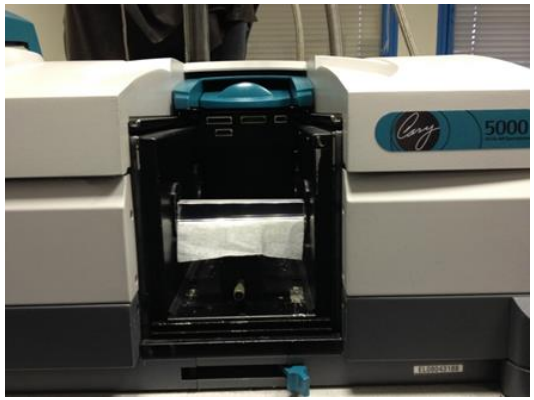
PANDA requirements
dk<1.1 after 30Gy

Radiation hardness of recent SICCAS crystals

Setting up infrastructure for crystal testing

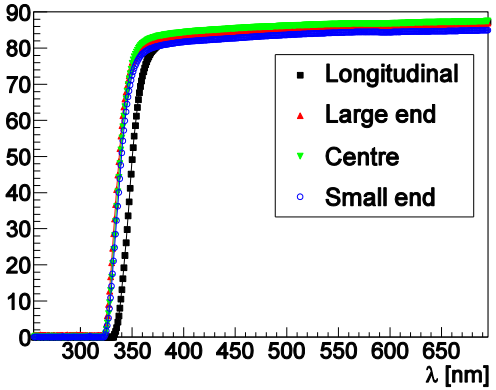
IPN-Orsay (France)

- Optical Transmittance (L/T)
  - Varian Cary 5000 spectrometer
  - Setup was commissioned with BTCP crystals on loan from Giessen
  - To accommodate crystals of lengths greater than 15 cm a more versatile configuration with a fiber-based spectrometer is being commissioned



Laboratoire de Chimie Physique (Orsay)

- Crystal light yield and timing
  - A setup is currently being tested with cosmic rays

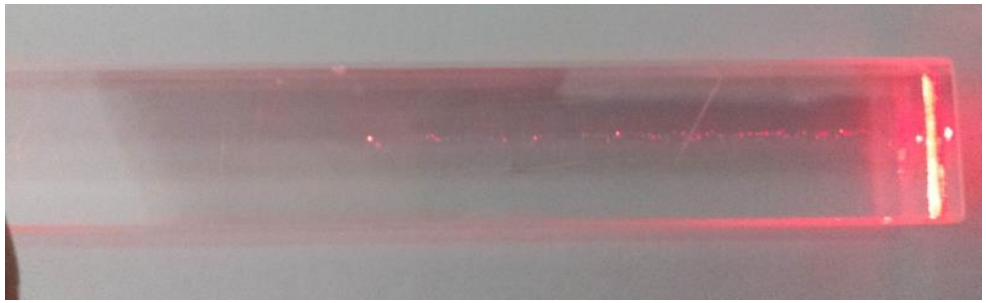


- Radiation Hardness
  - Panoramic irradiation facility available (^{60}Co sources):
    - 5000 Gy/h at 10 cm
    - 300 Gy/h at 35 cm
    - 6 Gy/h at 260 cm

At ~1m 30 Gy in ~30 min

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

Test of recent CRYTUR crystals

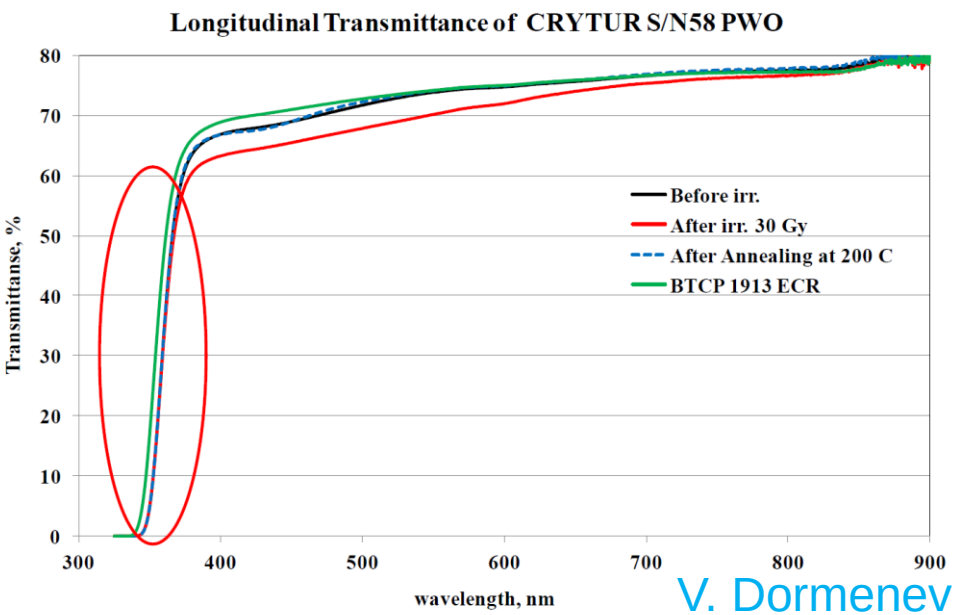


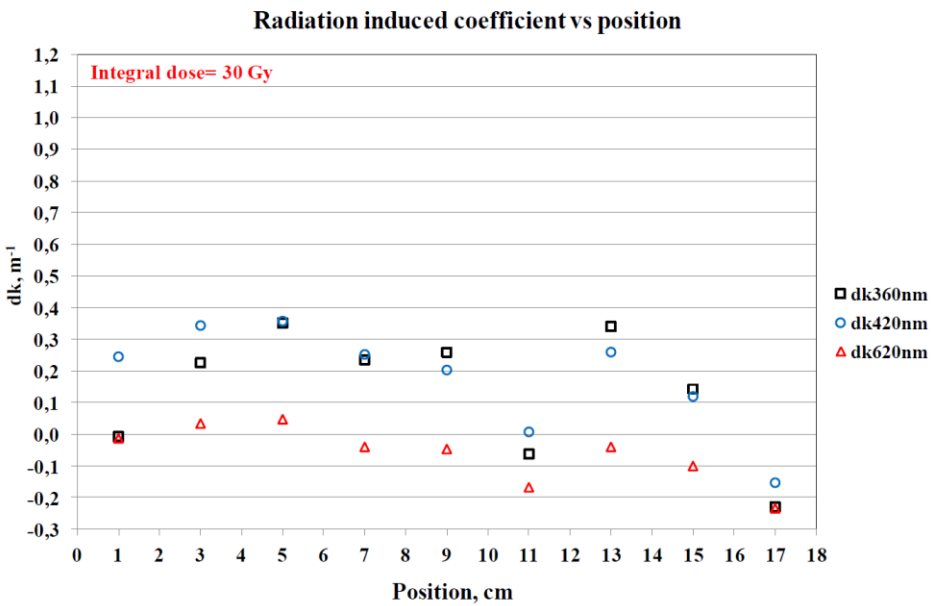
First full size (2x2x20 cm^3) crystal produced by CRYTUR (Oct 2015)

Grown in Ar atmosphere & doped with La+Y

- 3 new (2016) crystal with dimensions: 20x20x18.5 mm^3
- Low light yield (12-13 pe at 18°), with tolerable non-uniformity (maybe due to high doping)
- Acceptable tranmittance. Longitudinal transmittance **does not** show absorption band in the luminescense range
- Crystal similar to CMS quality

(shift of transmittance edge and low radiation induced coefficient)





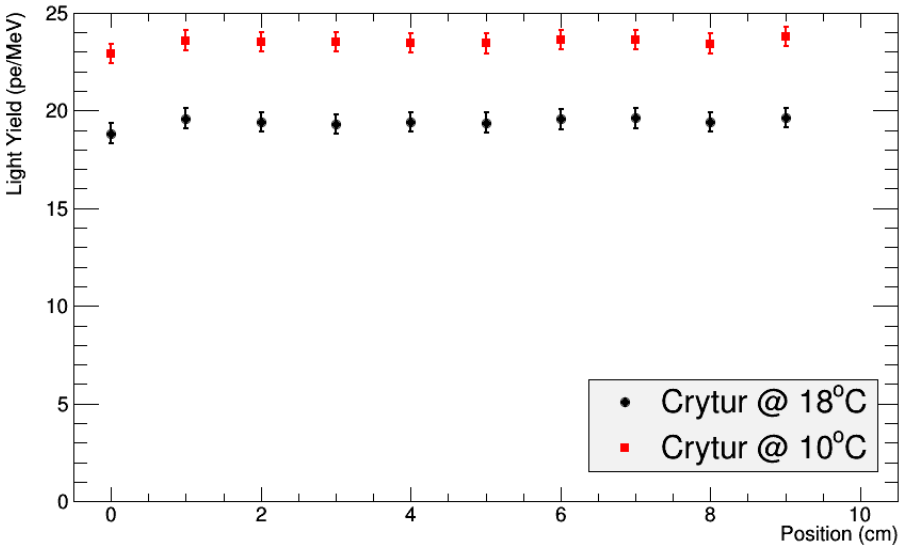
V. Dormenev

Setting up infrastructure for crystal testing

CUA (USA)

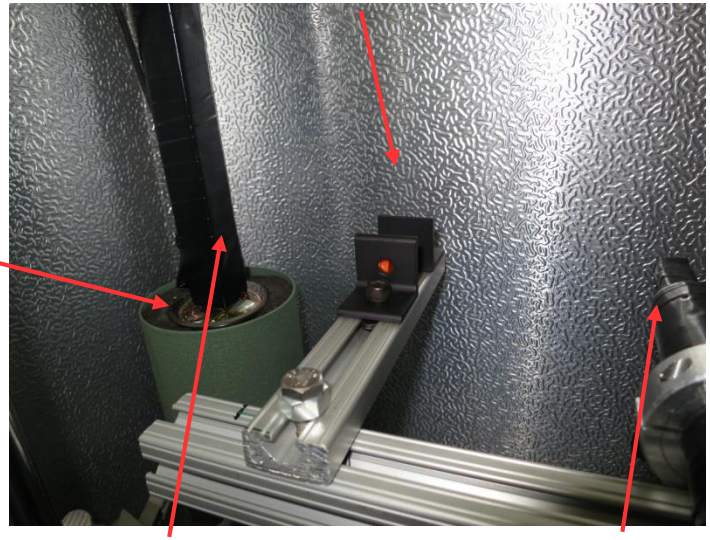
Light yield:

Temperature dependence



Temperature controlled dark box

Source of Na-22 (two 0.511 keV photons back-to-back)



PMT

Wrapped crystal

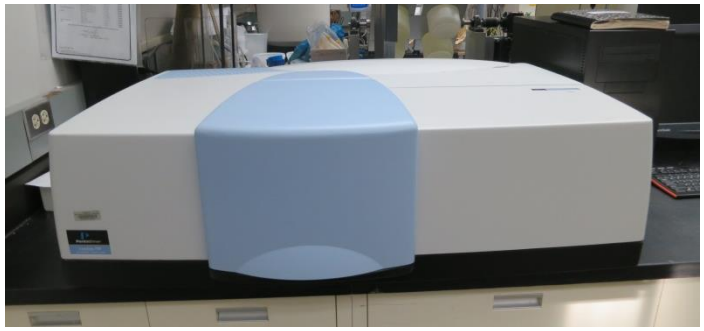
Trigger PMT

Comparison with Giessen measurement at 18°:

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

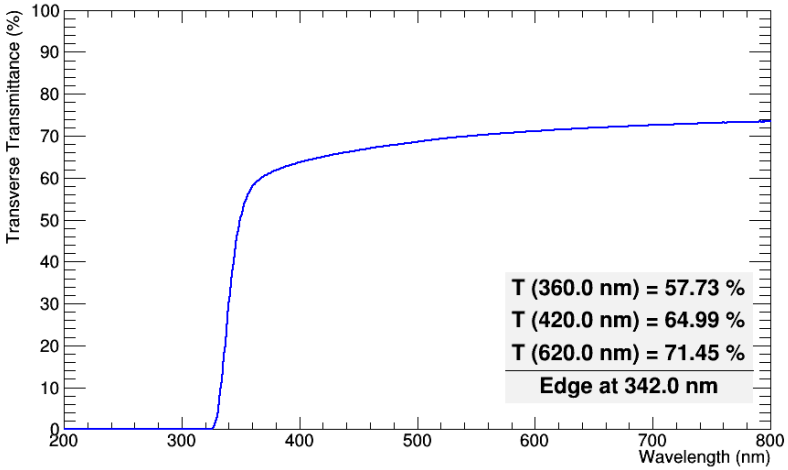
Warning: PMTs quantum efficiencies are similar, but probably different.

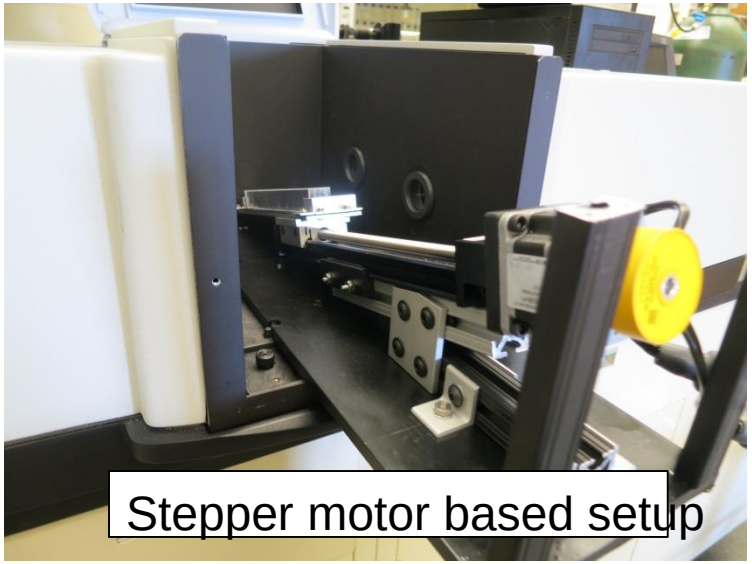
Light transmittance measurements at CUA



Lambda 750
UV/VIS/NIR

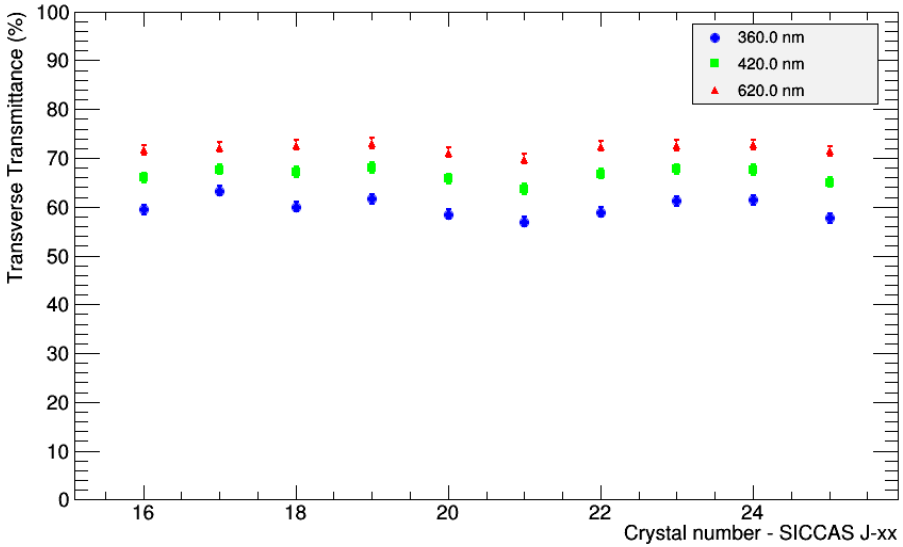
Transverse transmittance of individual crystal





Stepper motor based setup

Variation of crystals' transverse transmittance in the l



Other activities in progress

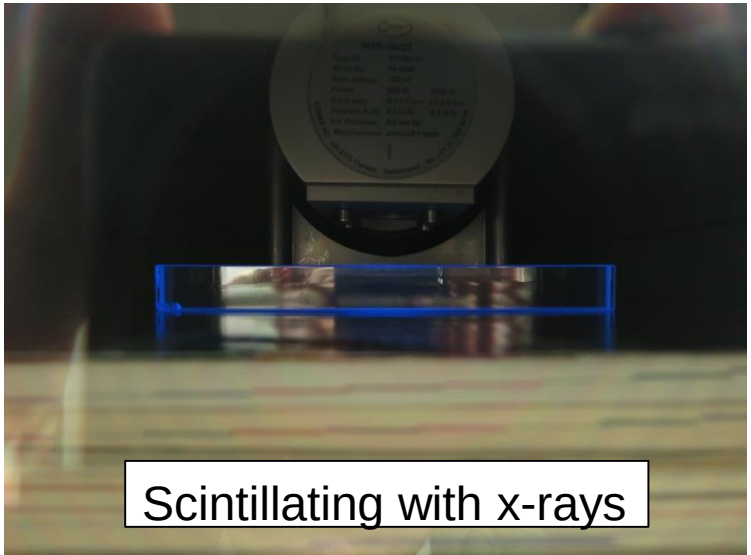
Radiation hardness

Lower energy range
(1-160 keV)

X-ray machine

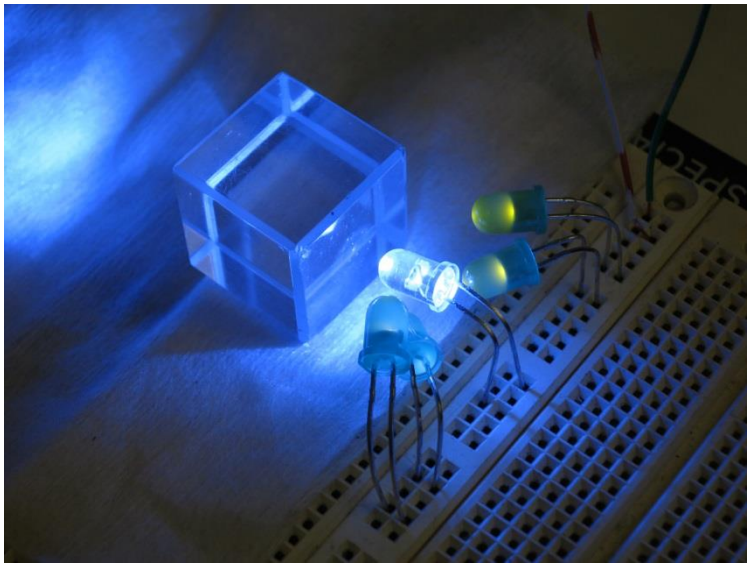
Intermediate energy
(1.17, 1.33 MeV)

0.5 mCi - Co-60



Scintillating with x-rays

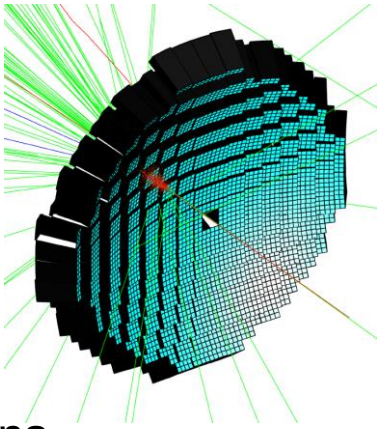
Light annealing (LED)



Thermal annealing (oven)

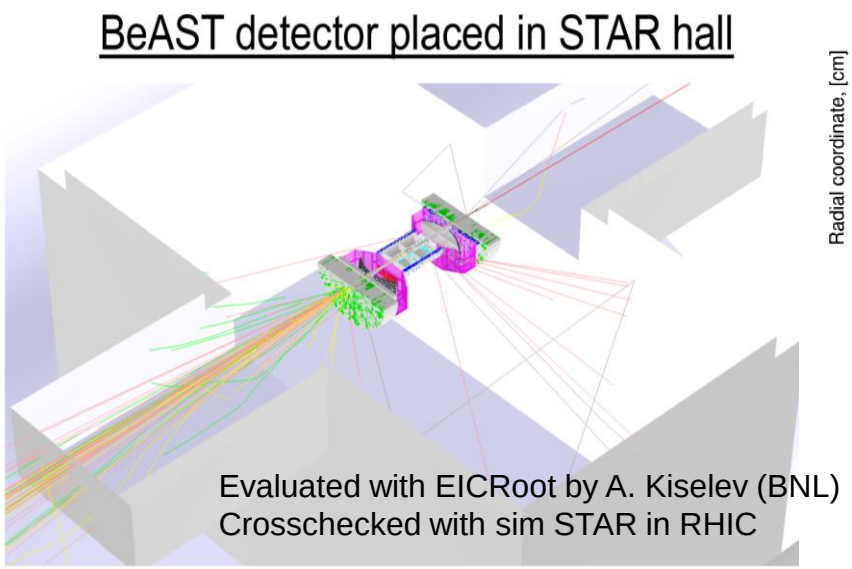
Calorimetry: simulations and radiation dose estimates

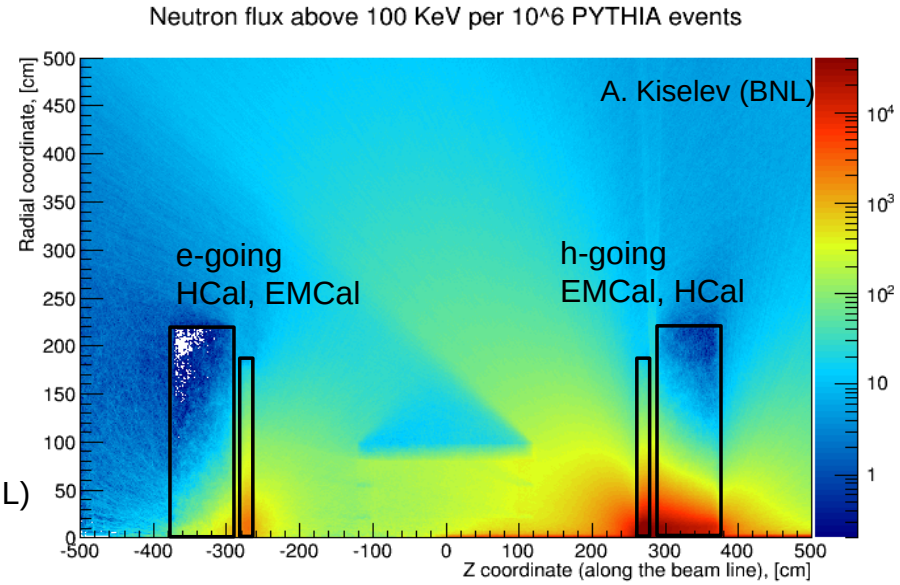
eRD1 also plays major roles in maintaining simulation & analysis frameworks, that is open source for full EIC detector simulation



EIC neutron fluence (as BeAST in eRHIC) calibrated to STAR

- Worst region in h-going calorimeter
  - 1 year EIC run ~ a few 10^{10} n_{eq}/cm^2 ~ 1 RHIC run
  - Challenging but possible for SiPM, also considering APD options
- e-going calorimeter and barrel calorimeter
  - ~ two order magnitude lower n-flux
  - Safe for SiPM operation





Summary and conclusions

eRD1 explores calorimeter technology for EIC in multiple fronts:

- Scintillation fiber calorimeter
  - Developed by UCLA group for EIC barrel and endcaps
  - Very promising results from recent test run at FermiLab
  - On-going R&D focus on higher energy resolution, mass-production capabilities and projectivities
- 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
- SiPM radiation tests, neutron background ≤ RHIC
- Full detector simulation environment open to users