Calorimeter Workshop Summary

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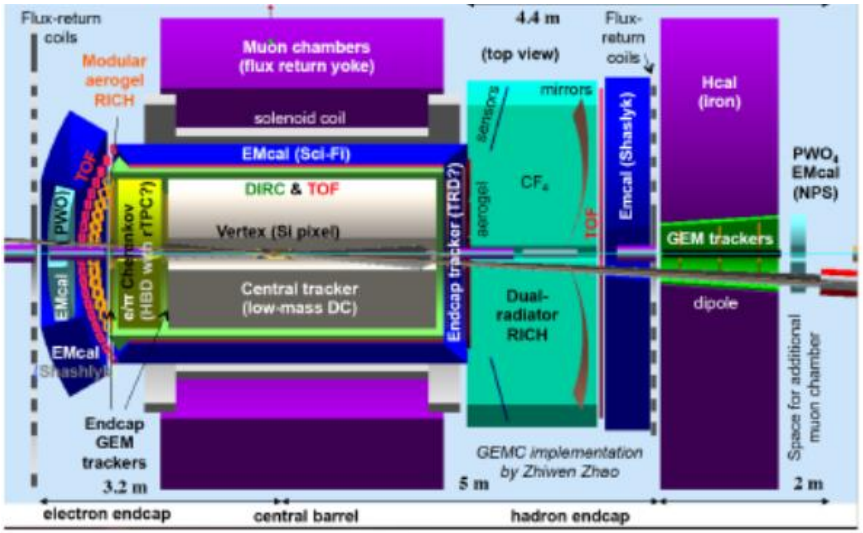
Introduction – Calorimeter Consortium Goals

Develop calorimeters that meet the requirements of physics measurements at an EIC – including all regions of the detector

Systematic uncertainties are expected to be the main limiting factor in extracting the underlying physics

- ***Reduce systematic uncertainty*** on a broad range of physics measurements by employing ***different technologies***
- Broaden the spectrum to include ***new technologies*** that could potentially offer ***improved performance, lower cost, mitigate risk and broaden user involvement***

Backward Barrel Forward



Workshop Organization

- Calorimeter Ad-Hoc Workshop on 6 April 2018 (https://indico.bnl.gov/event/4468/)
  - Phone meeting only
  - 8 presentations with much discussion
  - Workshop summary was circulated
  - Follow-up in person meeting planned
- Organizers:
  - Craig Woody, Tanja Horn, Ed Kistenev

EIC Calorimeter Workshop

Friday 6 Apr 2018, 13:00 → 15:00 US/Eastern

Description
To join the Meeting:
https://bluejeans.com/446422422

To join via Room System:
Video Conferencing System: bjn.vc -or-199.48.152.152
Meeting ID : 446422422

To join via phone :
1) Dial:
+1.408.740.7256 (United States)
+1.888.240.2560 (US Toll Free)
+1.408.317.9253 (Alternate number)
(see all numbers - http://bluejeans.com/numbers)
2) Enter Conference ID : 446422422

13:00	→ 13:10	**Introduction and Ongoing Projects** 10m **Speaker**: C. Woody (BNL) EIC_Calorimeter_Wo...
13:10	→ 13:22	**Shashlik Calorimeter Development** 12m **Speaker**: E. Kistenev (BNL) ShashlikDevelopme...
13:22	→ 13:34	**Silicon Calorimetry for EIC** 12m **Speaker**: J. Repond (ANL) EIC_Calorimeter_Ph...
13:34	→ 13:46	**Si-W Calorimetry at ALICE** 12m **Speaker**: M. van Leeuwen (CERN) 20180406_FOCAL_...
13:46	→ 14:00	**Discussion** 14m
14:00	→ 14:12	**BaF2 Status and Potential** 12m **Speaker**: R-Y. Zhu (Caltech) 4EIC_180406_BaF2...
14:12	→ 14:24	**Glass/Ceramics and New Materials** 12m **Speaker**: I.Pegg/T.Horn (CUA) EIC_Calo_6April201...
14:24	→ 14:36	**Hadron Calorimetry** 12m **Speaker**: O. Tsai (UCLA) OlegTsai_04062018...
14:36	→ 14:48	**Very Radiation Hard Forward Detectors for ILC** 12m **Speaker**: S. Schuwalov (DESY) Radiation hard sens...

Workshop Overview

- Requirements for the different EIC calorimeters, e.g. excellent energy resolution in the forward regions
- Overview of EIC calorimeter R&D in both, central and intermediate, and forward regions
- New cost effective detector materials for calorimeters in forward and central regions
- Technologies with possible application for EIC and auxiliary detectors like zero-degree calorimeter and luminosity monitors

Explore new types of calorimeter technology and detector materials of relevance to a future EIC and potentially establish new collaborations

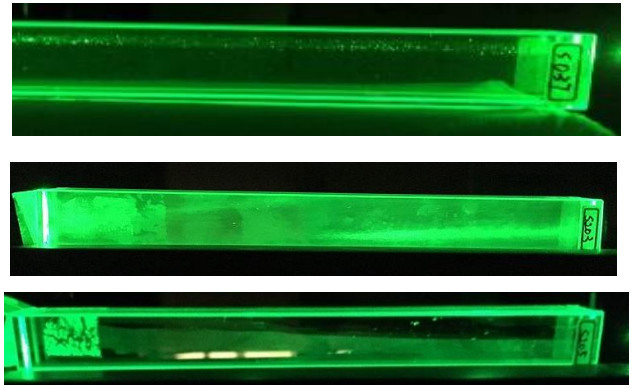
Summary and Future Plans for eRD1

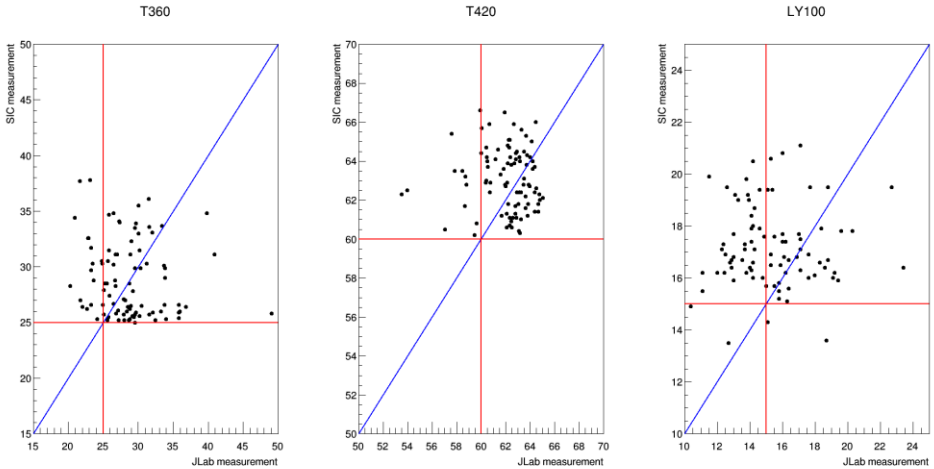
Status of current projects

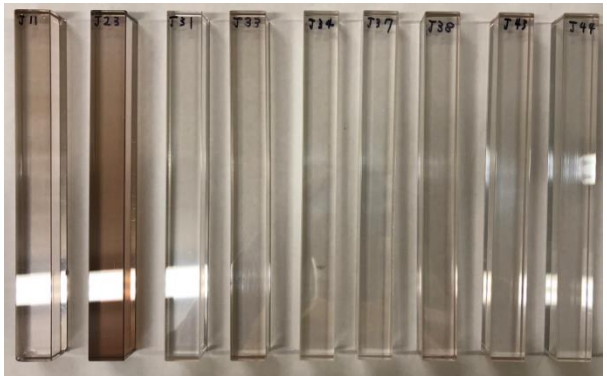
- W/SciFi calorimeter R&D
  - Early R&D lead to full implementation into sPHENIX detector
  - Now investigating alternative readout with WLS bars
  - Radiation damage studies of SiPMs is ongoing
- W/Shashlik calorimetry
  - Investigating as a possible alternative to W/SciFi calorimetry
- Hadron Calorimetry
  - Investigating dual readout HCAL measuring time development of hadronic shower
- Crystal Calorimetry
  - Study of PWO crystals is ongoing; continuing to investigate crystals from two possible vendors
  - New investigation of scintillating glass materials is beginning
- Investigating other forms of calorimetry
  - Particle flow, radiation hard, luminosity monitors, …

eRD1 Ongoing Projects: For/Backward and Very Forward

- **SICCAS**: ~40% of SICCAS 2017 crystals fail specs
  - Major categories for failure: LT@420nm or light yield (10%), bubbles and other defects (13%), chips/scratches (8%)
  - Meeting at SICCAS 23 July (https://halldweb.jlab.org/wiki/index.php/Meeting_with_SICCAS)







- **CRYTUR**: Considerable limitation in mass production
  - Limited to ~400 crystals/year – maxed out in 2018 due to PANDA order

Glass-based Scintillators for Detector Applications

An alternative active calorimeter material that is more cost effective and easier to manufacture than, e.g. crystals

Material/ Parameter	Density (g/cm^3)	Rad. Length (cm)	Moliere Radius (cm)	Interact Length (cm)	Refr. Index	Emission peak	Decay time (ns)	Light Yield (γ/MeV)	Rad. Hard. (krad)	Radiation type	Z_{Eff}
(PWO)$PbWO_4$	8.30	0.89 0.92	2.00	20.7 18.0	2.20	560 420	50 10	40 240	>1000	.90 scint. .10 Č	75.6
($BaO*2SiO_2$):Ce glass	3.7	3.6	2-3	~20		440, 460	22 72 450	>100	10 *(no tests >10krad yet)*	Scint.	51
($BaO*2SiO_2$):Ce glass loaded with Gd	4.7-5.4	2.2		~20		440, 460	50 86-120 330-400	>100	10 *(no tests >10krad yet)*	Scint.	58

Also: ($BaO*2SiO_2$):Ce shows no temperature dependence

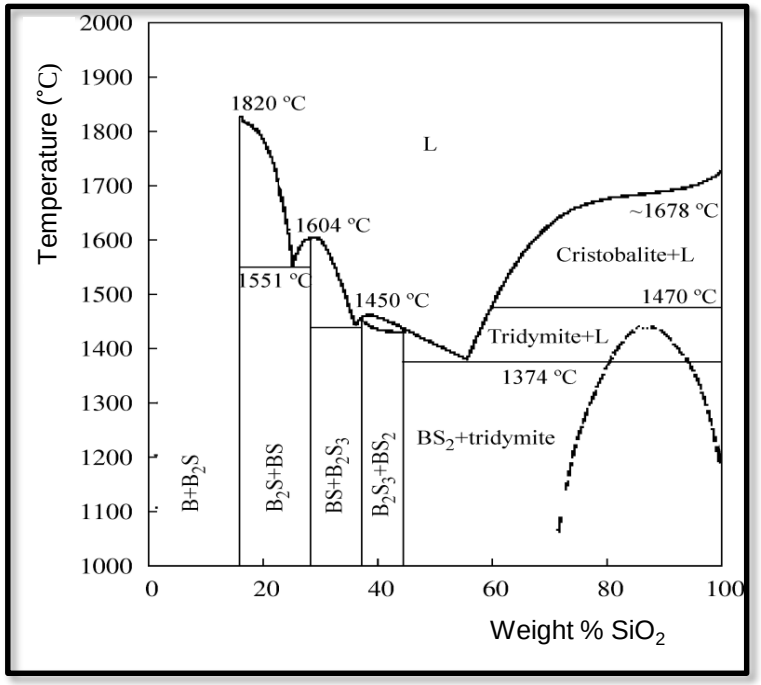
Shortcomings of earlier work:

- Macro defects, which can become increasingly acute on scale-up
- Sensitivity to electromagnetic probes

Material Overview

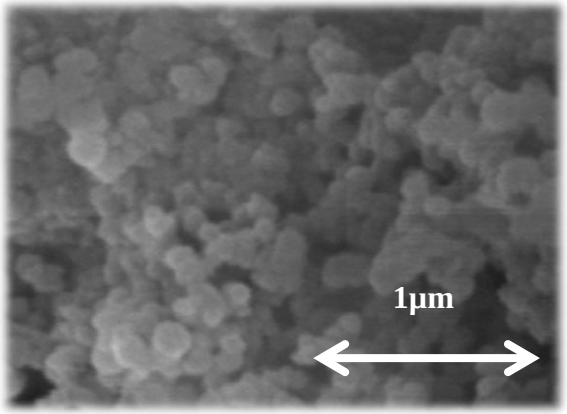
Technology: Glass production combined with successive thermal annealing (800 – 900°C)

Phase diagram of the $BaO*SiO_2$ system



Material	Density (g/cm³)	X_0 (cm)	Emission peak (nm)	Cutoff (nm)	Zeff
$(BaO*2SiO_2)$:Ce glass	3.7	3.6	440, 460	310	51
DSB:Ce	3.8	3.5	440, 460	310	51
$(BaO*2SiO_2)$:Ce glass loaded with Gd	4.7-5.4	2.2	440, 460	318	58

Study of New Glass and Glass Ceramics Scintillation Material (Novotny et al., 2016+)

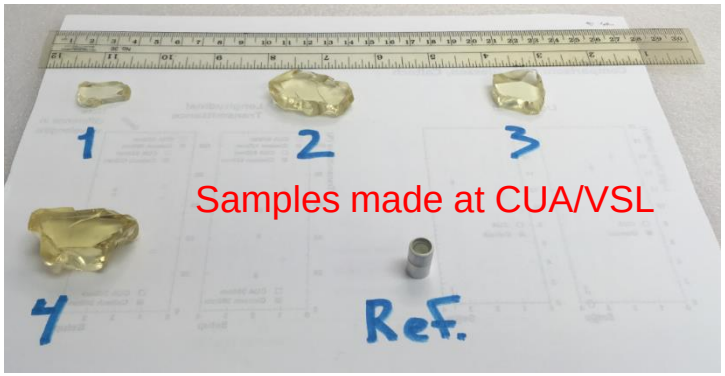


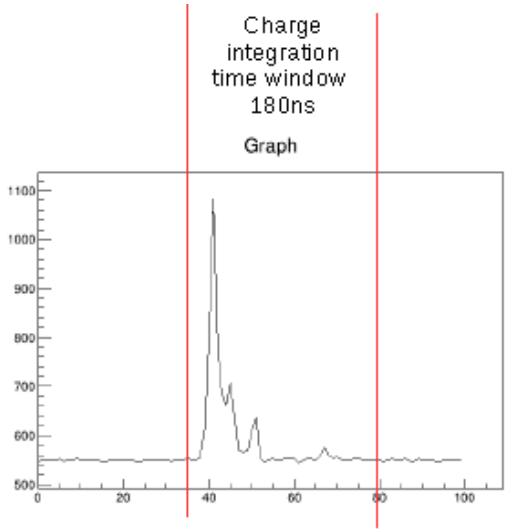
SEM image of recrystallized $BaO*2SiO_2$ at 950°C

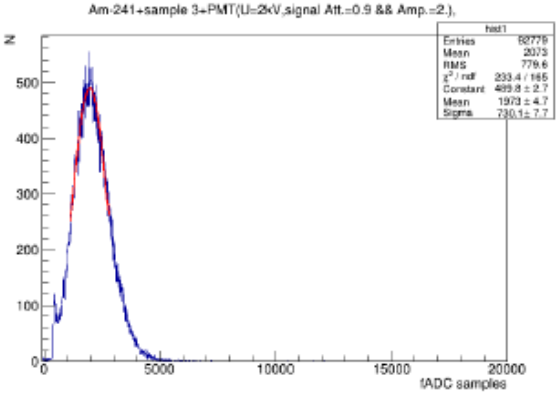
- Nano-sized particles of **$BaSi_2O_5$**
  - improve scintillation!
- Ba-Si system allows to incorporate trivalent ions: **Lu, Dy, Gd, Tb, Yb, Ce**

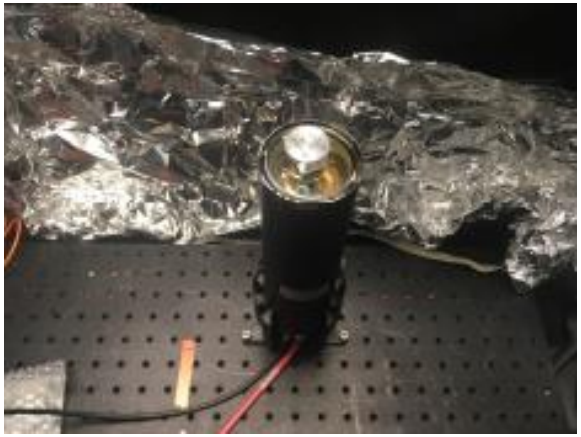
Status of New Glass/Ceramic Scintillator Material

- Optical properties, radiation resistance, light yield and temperature stability seem competitive, sometimes better than $PbWO_4$





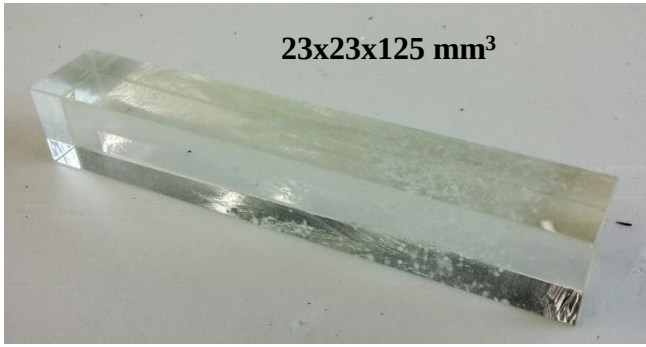


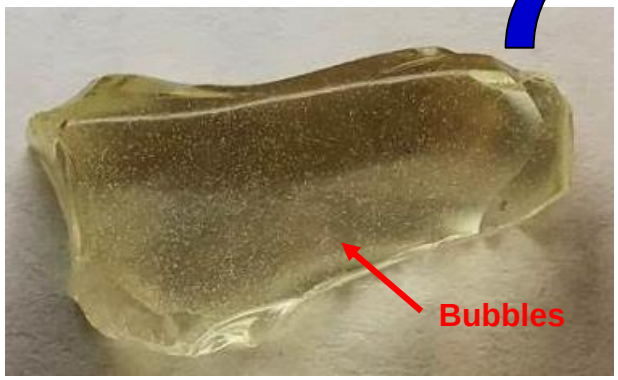


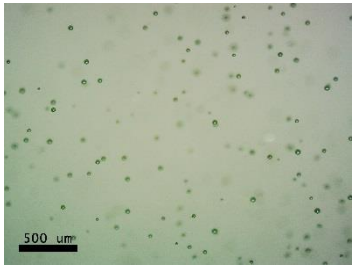
Material/ Parameter	$PbWO_4$	Sample 1	Sample 2	Sample 3	Sample 4
Luminescence (nm)	420	440	440	440	440
Relative light output (compared to $PbWO_4$)	1	35	16	23	11

Status of New Glass/Ceramic Scintillator Material

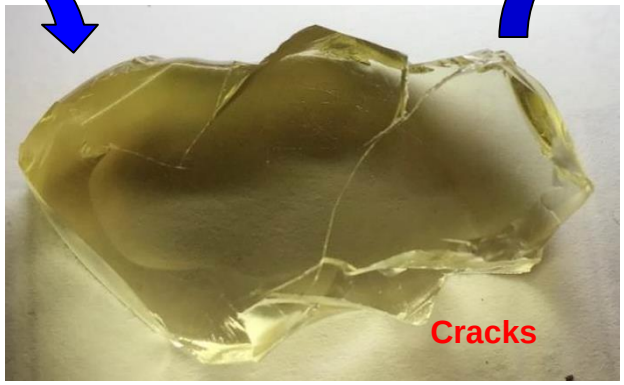
- Uniformity remains a concern – manufacturing process requires optimization – progress with new method at CUA/VSL

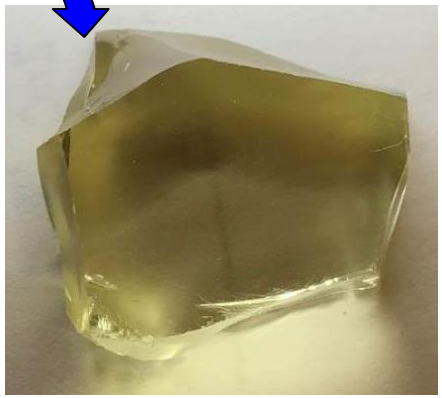


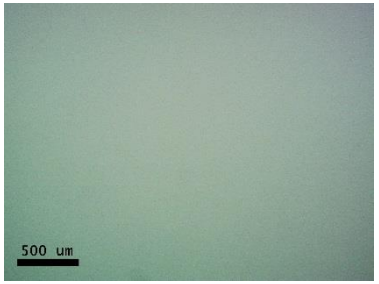




Sample made at CUA/VSL based on previous DSB:Ce work







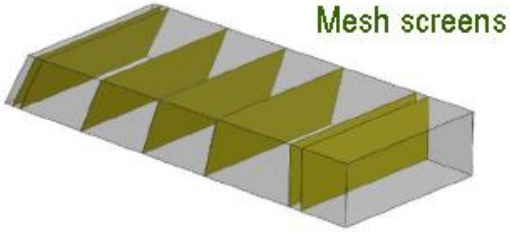
Samples made at CUA/VSL with our new method

eRD1 Ongoing Projects: Central and Mid- Region

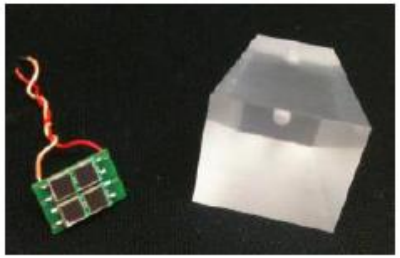
- W-powder/Scintillating fiber with SiPM readout

Developed ay UCLA (O.Tsai) and adopted for the sPHENIX EMCAL

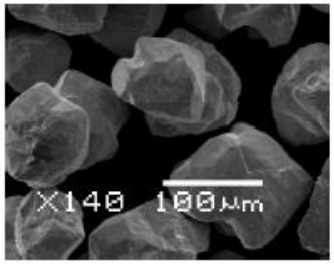
1D Projective



Read out with SiPMs



Matrix of tungsten powder & epoxy with embedded scintillating fibers



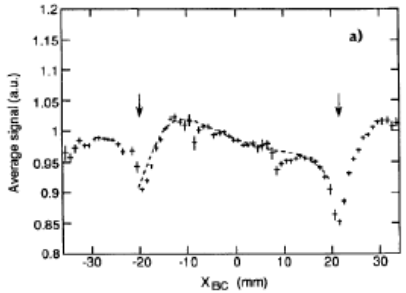
- Early R&D for the central/barrel region is essentially complete

eRD1 Ongoing Projects: Central and Mid- Region

Uniformity of response

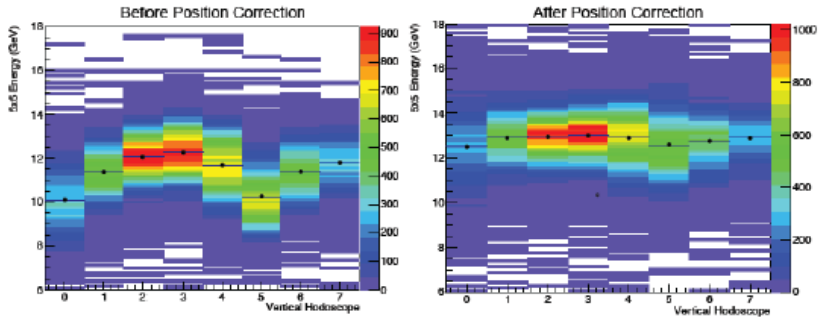
Non-Uniformities at block boundaries are an inherent property of SPACALs

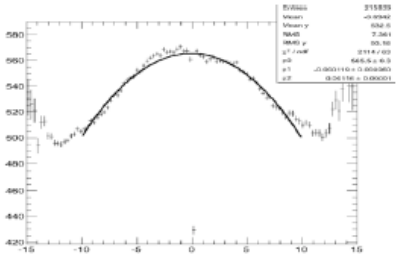
- Fibers essentially channel light to the photodetector.
- Rely on light guide to mix and randomize the light
- Difficult to do when there is limited space and limited photocathode coverage



Original SPACAL (Wigmans 1995)

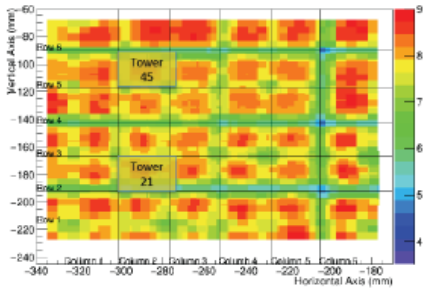
sPHENIX 1D Projective



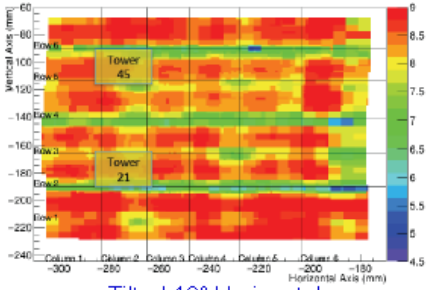


2014 Test Beam Data (UCLA)

sPHENIX 2D Projective



0° Horizontal



Tilted 10° Horizontal

❑ High density Shashlik

- ➢ Path forward to address non-uniformities and improve energy resolution for measuring jets and providing PID for SIDIS and DVCS

eRD1: Hadron Calorimeter

HCals (EM) R&D, Technology Wise (not a complete list, examples).

- HERA – compensation <- large scale R&D
- LHC - radiation hardness, (large scale R&D Crystals and APDs HEP)
- EIC Calor R&D, in general, adopting new technologies, improving construction techniques, relatively **small scale** efforts. Expected to be continued at the same level.

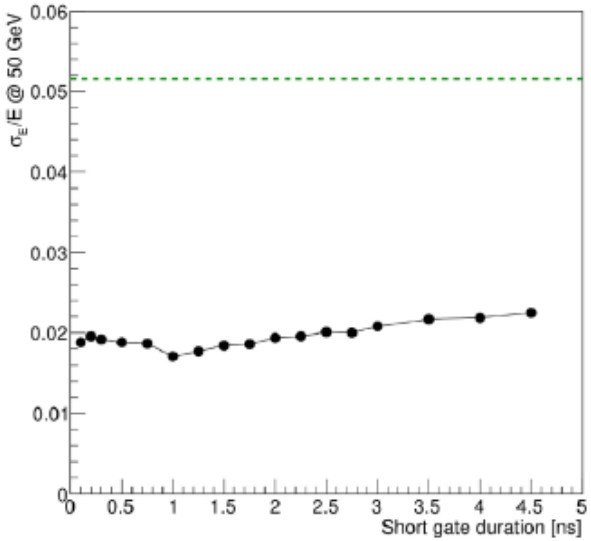
What new can we do?

SPACE -TIME EVOLUTION OF HADRON SHOWERS AND ITS USE IN HADRON CALORIMETRY E. Auffrey, A.Benaglia, P. Lecoq, M. Lucchini, A.Para, H. Wenzel

CPAD WORKSHOP

October 10, 2016

Also TICAL ERC Grant, P. Lecoq et al



- Compensation – cost, neutrons (SiPMs)
- 'Timing approach' does not require compenstaion.
- Not a small scale effort to get proof of idea!
- Required prototype 0.6m x 0.6m x 9 int. length. + fast WFD.

Had to be some sort of staging:

Step I (STAR Forward + cold QCD) FNAL test run 2019. Small 0.4 m x 0.4 m 5 int lenghth Fe/Sc + EM sections made of W/ScFi (re-use) and Pb/Sc (shashlyk, re-use). EIC objectives, have comparison of three configurations (all shown in one way or another at Jlab and BNL detector desighns).

Step ii. Extend prototype to 0.6 x 0.6 x 9 int. length, to get proof of idea (borrow STAR forward HCal parts, should be in production in 2019).

eRD1: Auxiliary Detectors

- Examples:
  - Luminosity monitors
  - Low Q^2 tagger – close to beamline, must be radiation tolerant
  - Zero-Degree Calorimeter (ZDC) – detect forward going hadrons

- Possible concept strategies:
  - Very radiation hard detectors - ILC FCAL
  - Si-W - ALICE
  - Very radiation resistant $PbWO_4$ - PANDA

Radiation hard sensors for HEP calorimetry

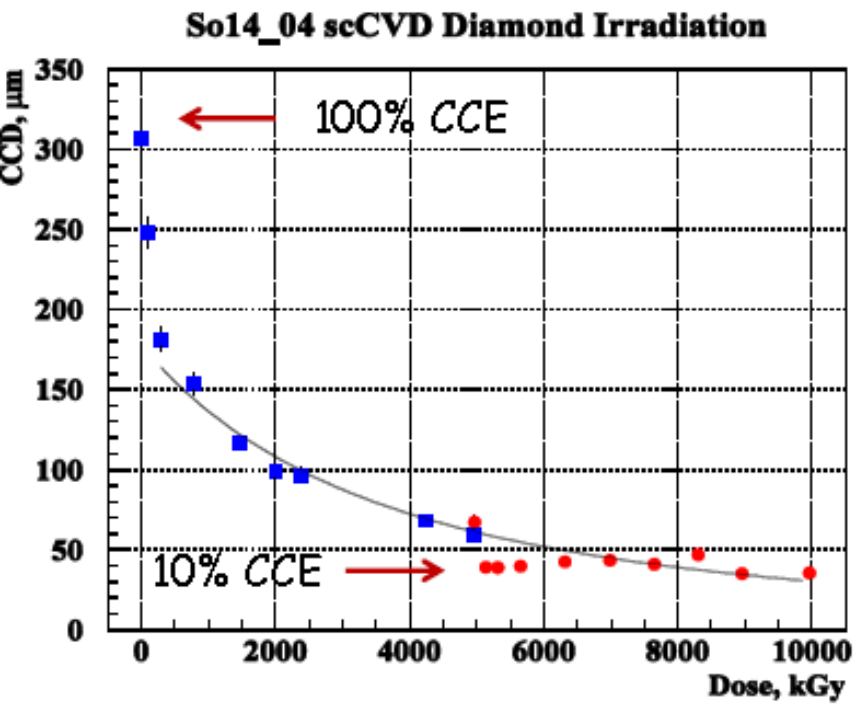
Sergej Schuwalow, DESY Hamburg

Goals and ideas for ILC near beam calorimetry

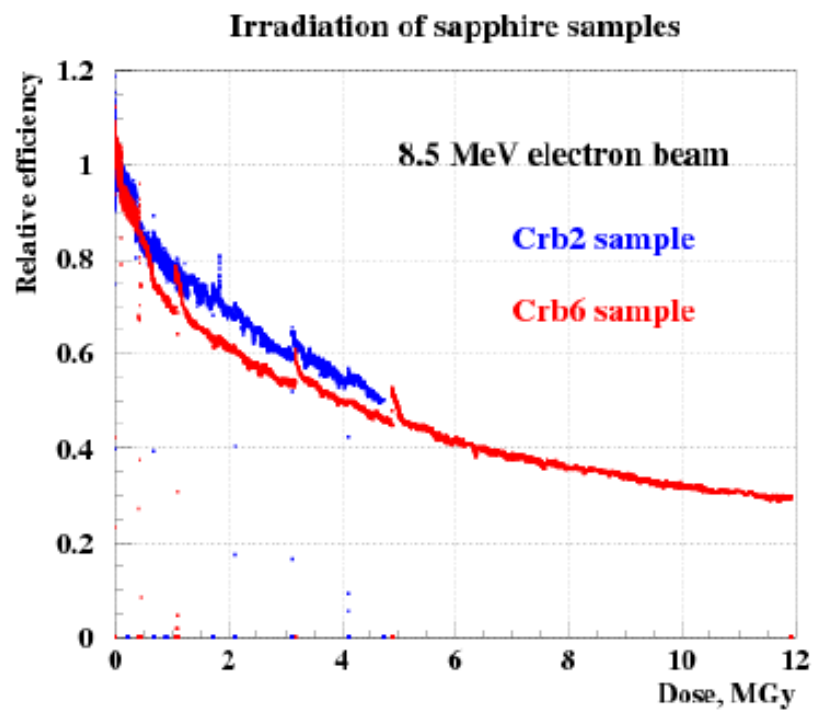
- For the future e+e- linear collider intensive beamstrahlung due to bunch-bunch interactions is expected
- Very forward region (~5 – 50 mradian cone) after each collision contains several tens of thousands e+e- pairs of ~GeV energies (in total carrying ~ 10 TeV energy/BX)
- We would like to instrument very forward region with the special calorimeters (BeamCal) – important for new physics search and beam control/tuning purposes.
- Small Moliere radius is essential – the choice is the sampling calorimeter with tungsten absorber and solid state sensors
- Expected dose for the hot regions of BeamCal is ~ 1 MGy/year, for 10 years lifetime it translates to 10 MGy (1 Grad) dose for sensors to withstand

Irradiation of sapphire and diamond sensors at ~10 MeV electron beam

Single crystal CVD diamond



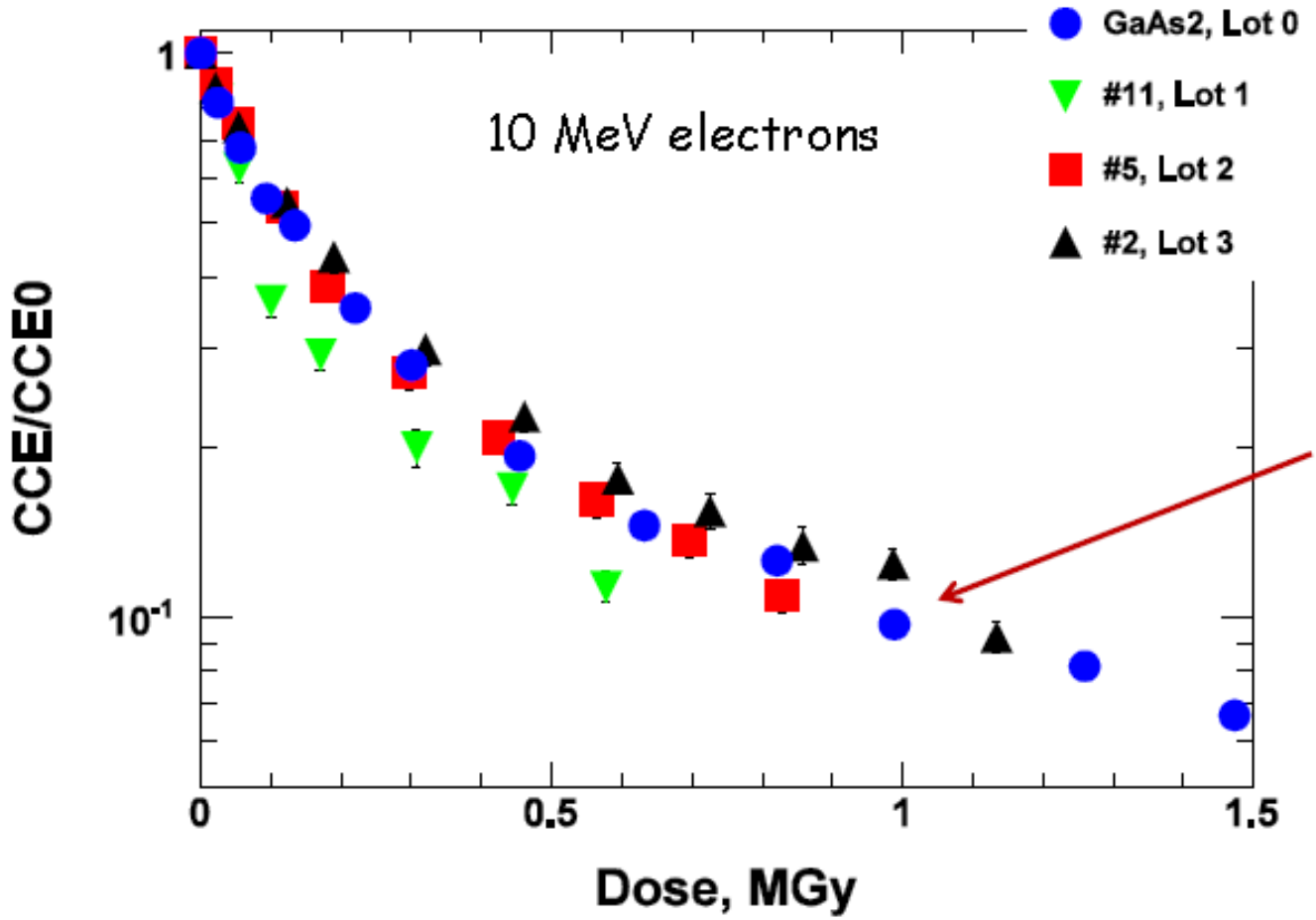
Single crystal sapphire



Leakage current after irradiation is still at few pA level

10 MGy ~ $5 \cdot 10^{16}$ MIPs ~ $2.5 \cdot 10^{15}$ [1 MeV neq] (NIEL,Summers)

Irradiation of GaAs sensors



Few μA leakage current after 1 MGy dose (extra noise!)

Marco van Leeuwen and Thomas Peitzmann
Nikhef, Utrecht University and CERN

FoCal-E design concept: Si-W calorimeter

Main challenge: separate γ/π^0 at high energy

- Need small Molière radius, high-granularity read-out

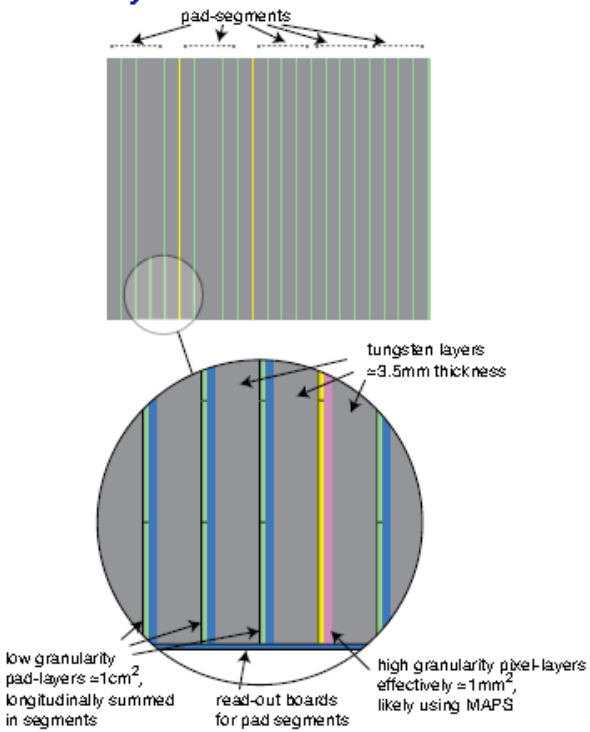
Combination of

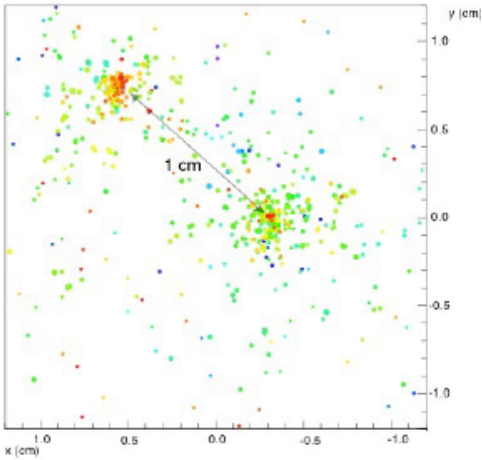
- Silicon pad readout 1x1 cm
- 2 pixel layers after 5 and 10 X_0

PAD layers:
analog readout for energy resolution

Pixel layers:
high granularity for two-shower separation

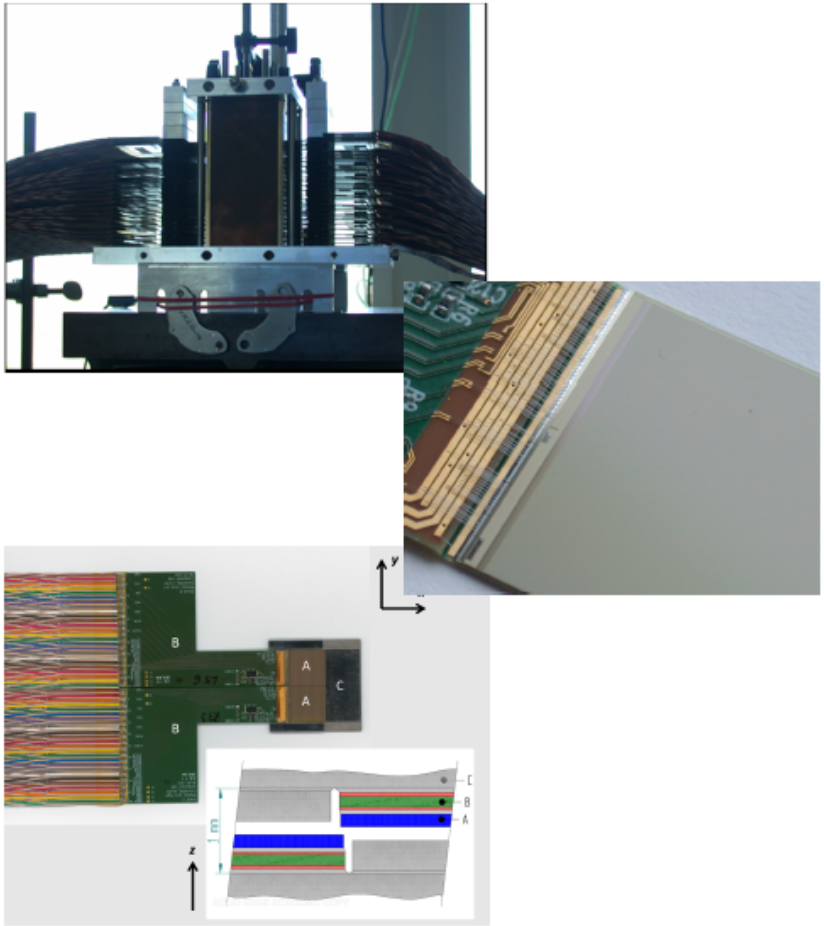
Under discussion in ALICE
for installation in LS3 (2024)





Two-shower event
electron test beam

High-Granularity Digital Calorimeter Prototype



R&D in the context of FoCal in ALICE

- 4x4x10 cm^3 prototype
- Si-W sampling
- 24 layers (1 X_0 W, MIMOSA23 sensors)
- pixel pitch 30μm – 39 million pixels

extremely compact design

- small Molière radius (R_M = 10.5 ± 0.5 mm)

choice of MIMOSA sensor

- high-granularity and full-frame readout
- extremely slow
  - 640μs per frame, integrating
  - continuous data stream of 8GB/s

preparing next generation prototype (ALPIDE)

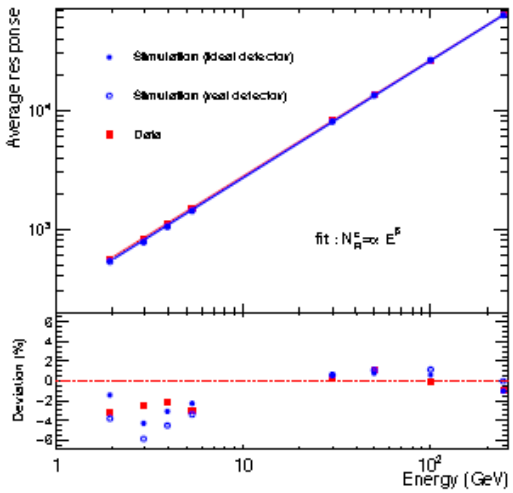
- faster, gated, radiation hard, …
- adequate for ALICE event rates

successful proof of principle

general application needs faster sensor!

R&D - Test Beam Performance

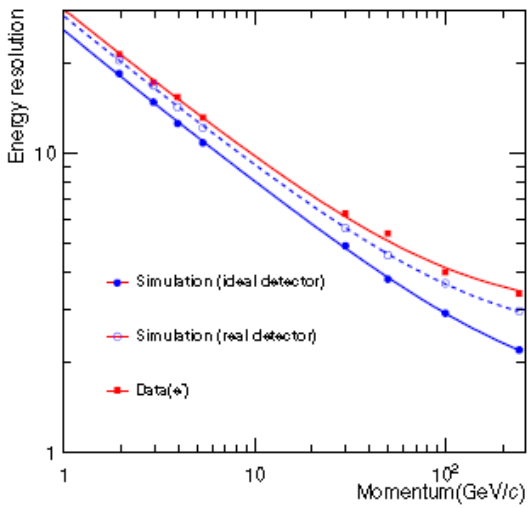
energy linearity



good linearity
(power law with $\beta = 0.98$)

- possibly different absolute calibration at low energy (not corrected)

energy resolution



reasonably good energy resolution
(includes 30% dead sensors)

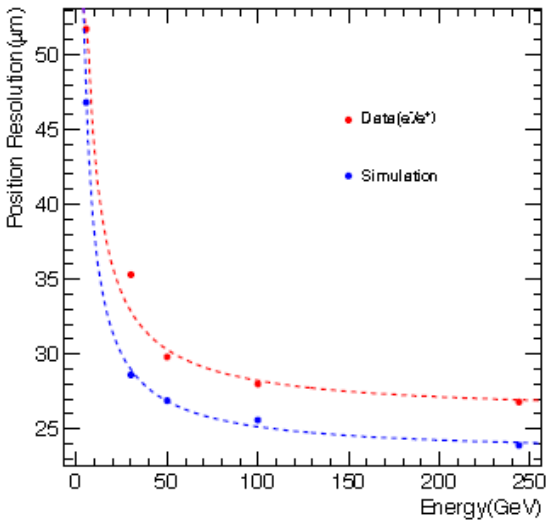
$$\frac{\sigma_E}{E} = a \oplus \frac{b}{\sqrt{E/\mathrm{GeV}}} \oplus \frac{c}{E/\mathrm{GeV}}$$

$a = (2.95 \pm 1.65)\%$

$b = (28.5 \pm 3.8)\%$

$c = 6.3\%$

position resolution



extremely good position resolution

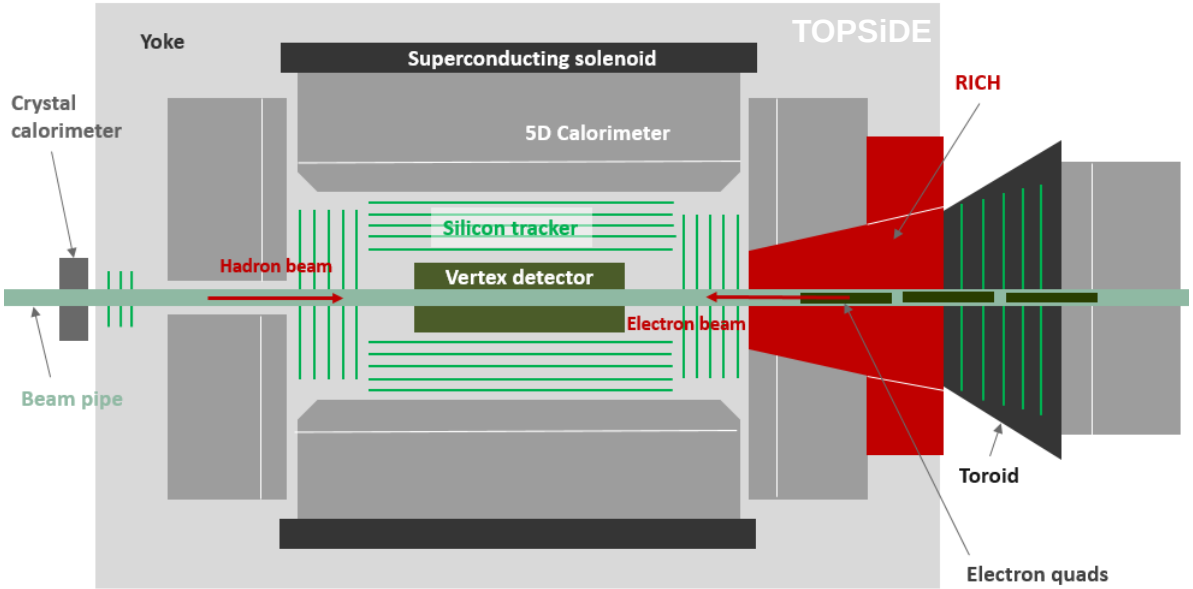
- not yet corrected for beam divergence and reference position resolution

See also: A.P. de Haas et al, JINST 13 (2018) no.01, P01014

TOPSiDE: Concept of an EIC Detector

5D Concept

Energy E
Position x,y,z
Time t



Salient features

4π detector (hermetic coverage)
Multi-purpose detector (don't need another specialized detector)
Mostly based on silicon sensors (tracker, electromagnetic calorimeter)
Each particle measured individually (optimized for Particle Flow Algorithms)
Particle identification (pion-kaon separation) performed by TOF (tracker and calorimeter)
Imaging calorimetry (tens of millions of readout channels)
Coil on the outside (not to disturb calorimetric measurements)
Dipole/Toroid in the forward direction (to obtain a momentum measurement)
Special detectors in the forward direction (Ring Imaging Cerenkov for Particle ID, debris taggers)

ULTRA – FAST SILICON

Needed for 5D Concept

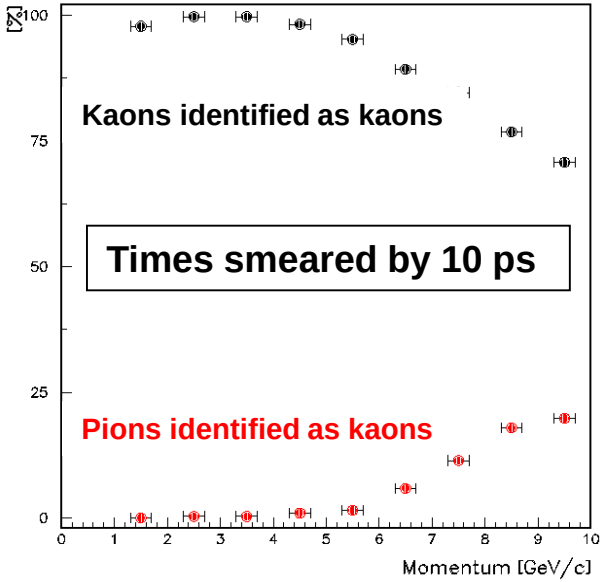
Implement in calorimeter and tracker for Particle ID
(π – K – p separation)
Resolution of 10 ps → separation up to ~ 7 GeV/c

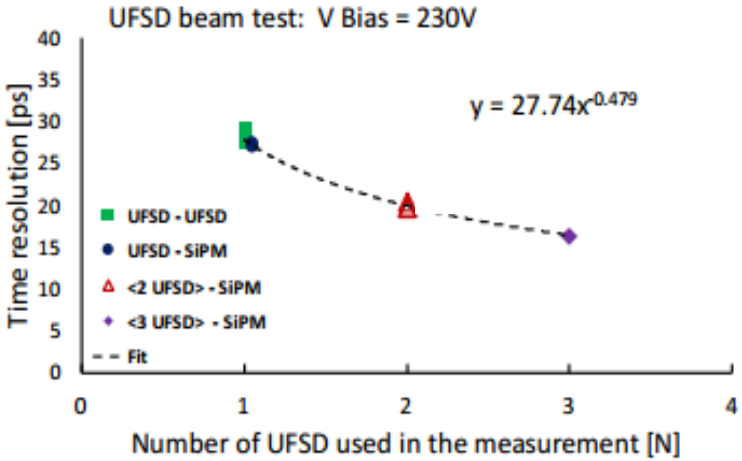
Current status

Being developed based on the LGAD technology
Best timing resolution about 27 ps

Future

Further improvements ongoing
→ Several groups worldwide





HCAL: RPC - Steel

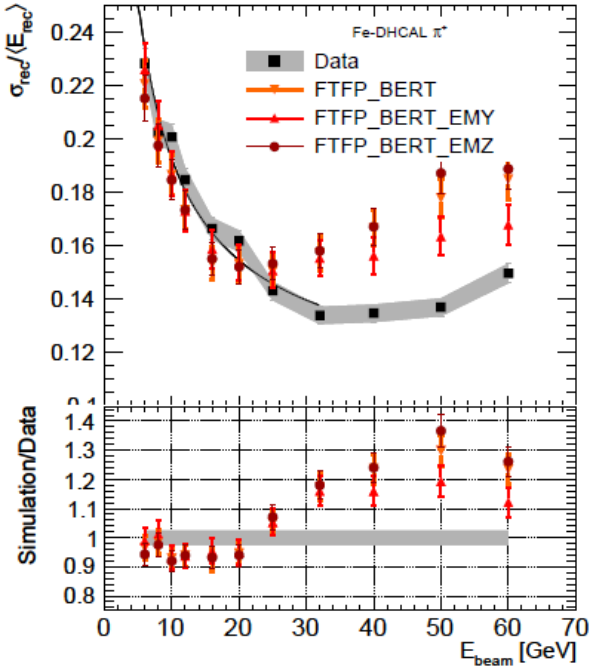
Resistive Plate Chambers – RPCs

Old, proven, reliable technology
Pros: cheap, fine readout segmentation possible
Cons: rate limited (typically < 100 Hz/cm^2, requires HV (~7kV)

Prototype – the DHCAL

Large prototype with 0.5M channels designed, constructed and tested
Readout with 1 x 1 cm^2 pads
Readout with 1-bit/channel → 'digital'
Digitization embedded in calorimeter
→ Extensive test in FNAL/CERN test beams

→ **Mature technology**



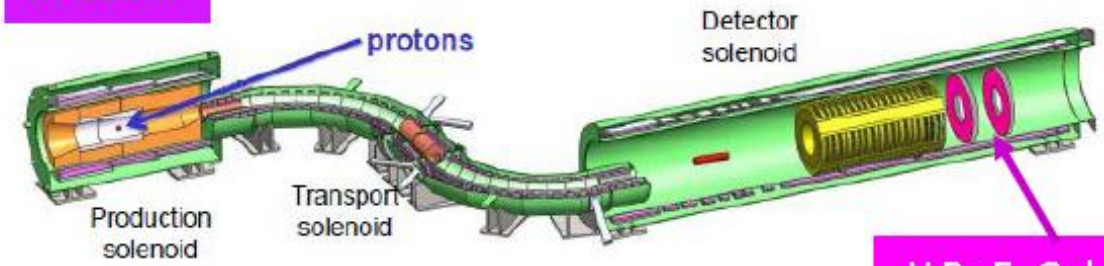
Further developments

Semiconductive glass → Increased rate capability (×50)
1-glass RPCs → thinner design
→ unit pad multiplicity/MIP
→ higher rate (×2)
Gas recycling → saves on operation cost
→ protects environment

Ultrafast Barium Fluoride Applications

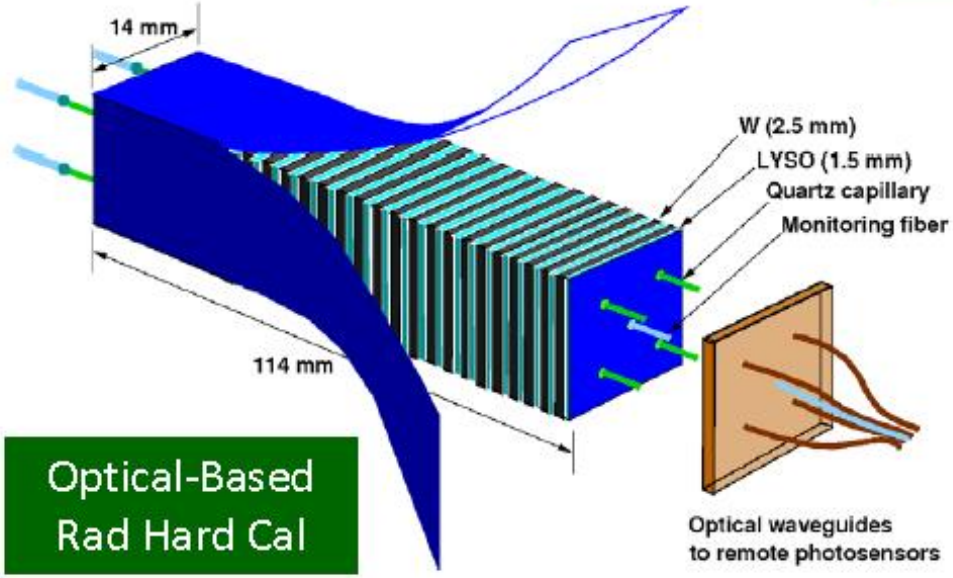
With sub-ns decay time/FWHM pulse width and excellent radiation hardness BaF_2 is an ultrafast inorganic scintillator for future HEP calorimeters at the energy and intensity frontiers

Mu2e-II



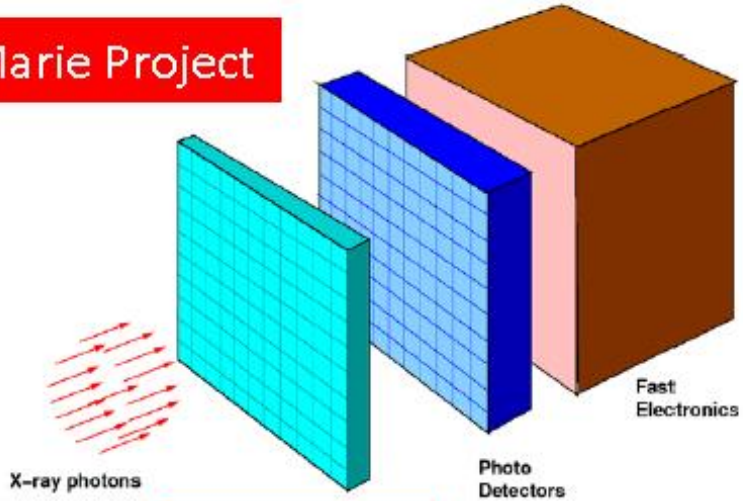
Y:BaF_2 Cal

Y:BaF_2 is also attractive for an ultrafast front imager for the FEL based GHz hard x-ray imaging



Optical-Based Rad Hard Cal

Marie Project

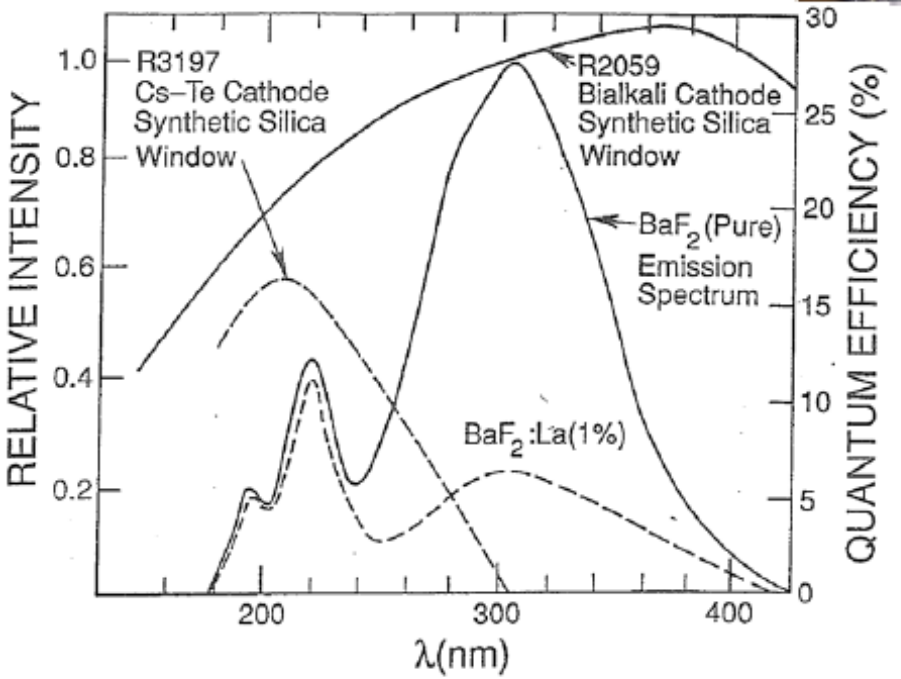


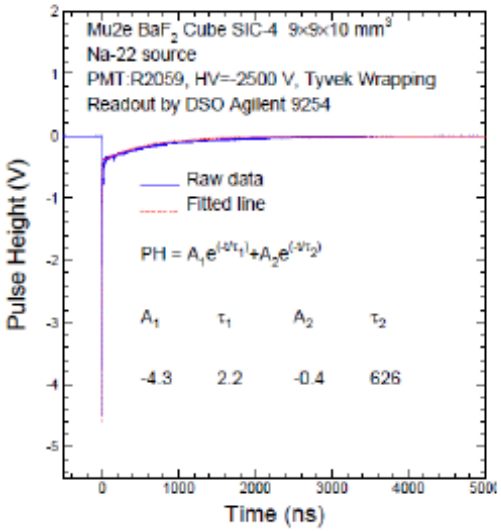
Y:BaF_2 Screen

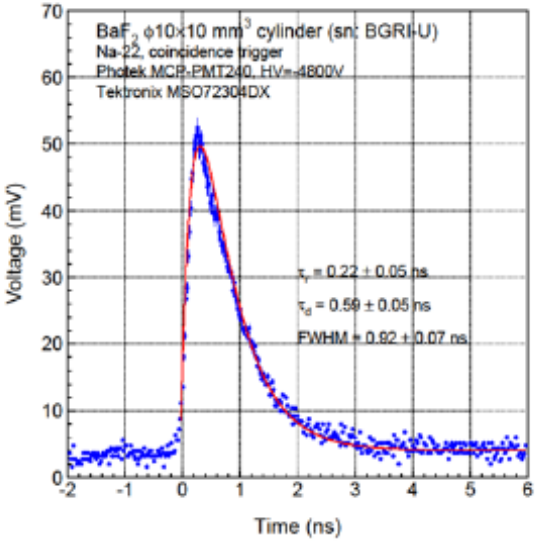
Fast and Slow Light from BaF_2

The fast component at 220 nm with 0.6 ns decay time has a similar LO as undoped CsI.

Spectroscopic selection of fast component may be realized by solar blind photocathode and/or selective doping.

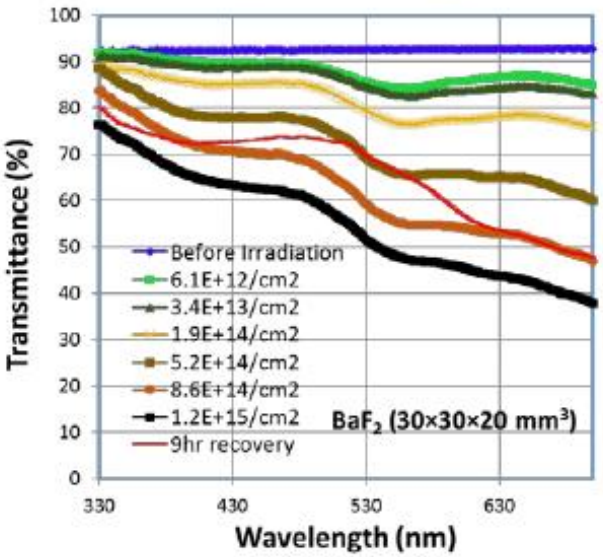


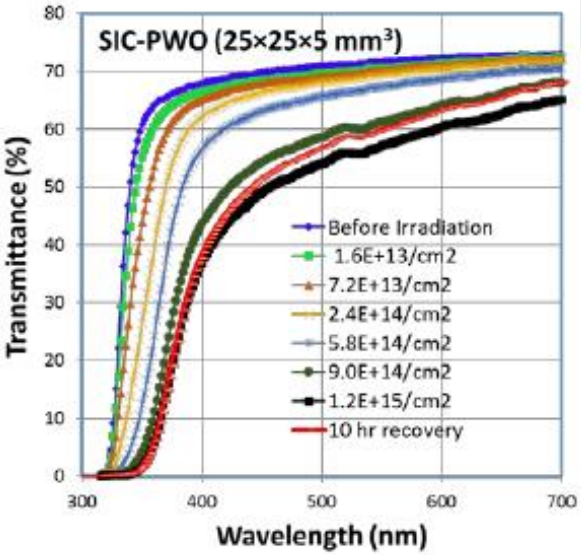


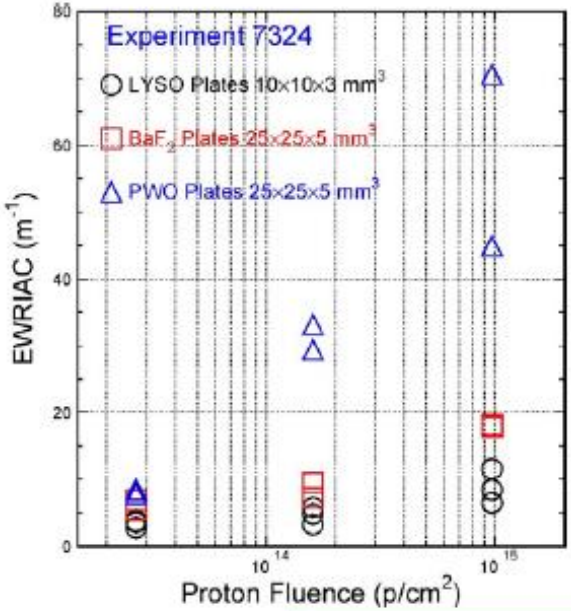


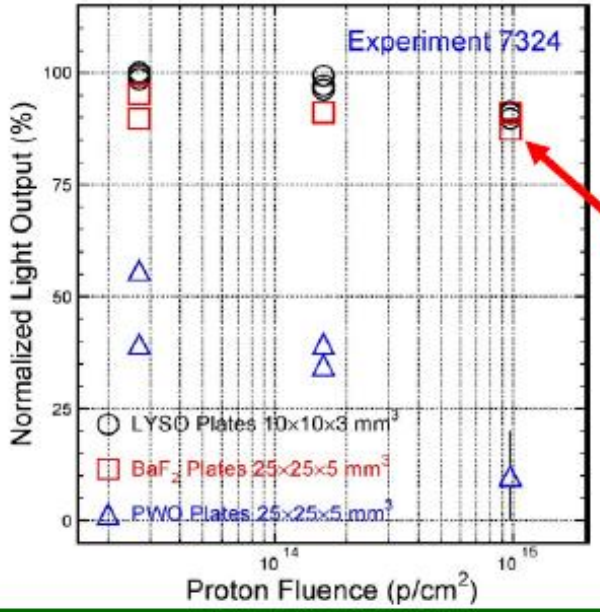
Protons: LYSO/BaF_2/PWO at LANSCE

A Hellma BaF_2 of 2 cm and a SIC PWO of 5 mm were irradiated up to 1.2×10^{15} p/cm^2 by 800 MeV protons at the blue room of LANSCE with transmittance measured *in-situ*.









LYSO, BaF_2 and PWO plates of 3, 5 and 5 mm were also irradiated up to 1×10^{15} p/cm^2.

Excellent radiation hardness observed in LYSO and BaF_2, but not PWO.

Proton-Induced Radiation Damage in BaF_2, LYSO and PWO Crystal Scintillators, IEEE TNS **65** (2018)
Digital Object Identifier 10.1109/TNS.2018.2808841

Guidance for path forward

- Initial R&D for the central region EIC calorimeters is essentially complete. Main issue seems space and cost, while maintaining radiation tolerance
- Forward R&D is making progress. Excellent resolution in energy and position is required. Works needs to continue with PbWO4 vendors and on understanding and reducing the constant term
- Development of cost effective, high performance material is essential
- Suitable technologies for auxiliary detectors needs to be identified and evaluated

A follow-up workshop to further discuss the different opportunities and explore synergies with university and laboratory groups is planned