RADiCAL – Precision-timing, Ultracompact Radiation-hard Elecromagnetic Calorimetry

T. Barbera, K. Ford, A. Heering, C. Jessop, Yu. Musienko, R. Ruchti, D. Ruggiero,

D. Smith, M. Vigneault, Y. Wan and M. Wayne

University of Notre Dame

T. Anderson, N. Chigapurupati, B. Cox, M. Dubnowski, R. Hirosky, A. Ledovskoy and C. Perez Lara

University of Virginia

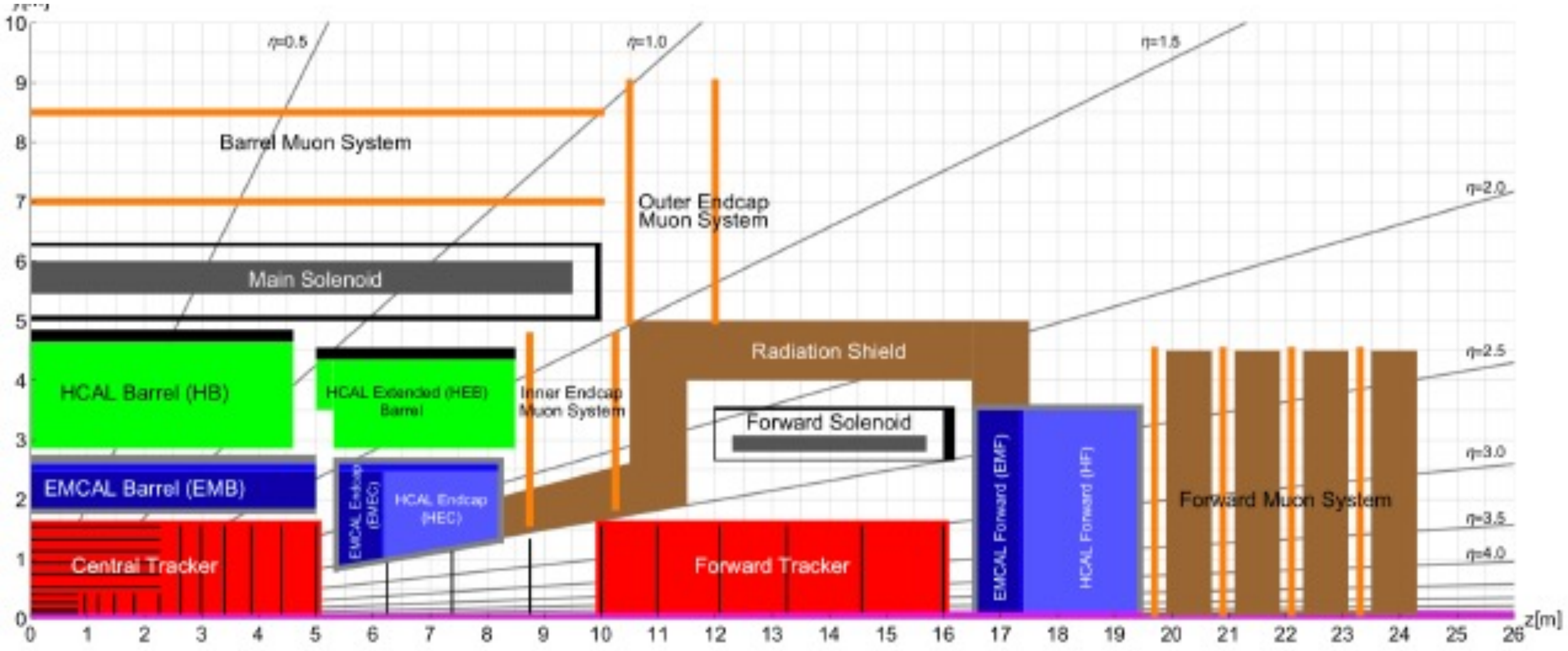
C. Hu, L. Zhang and R-Y. Zhu

California Institute of Technology

U. Akgun, P. Debbins, D. Blend, M. Herrmann, G. Karaman, O. Koseyan,

M. Mohammed, Y. Onel, and J. Wetzel

University of Iowa

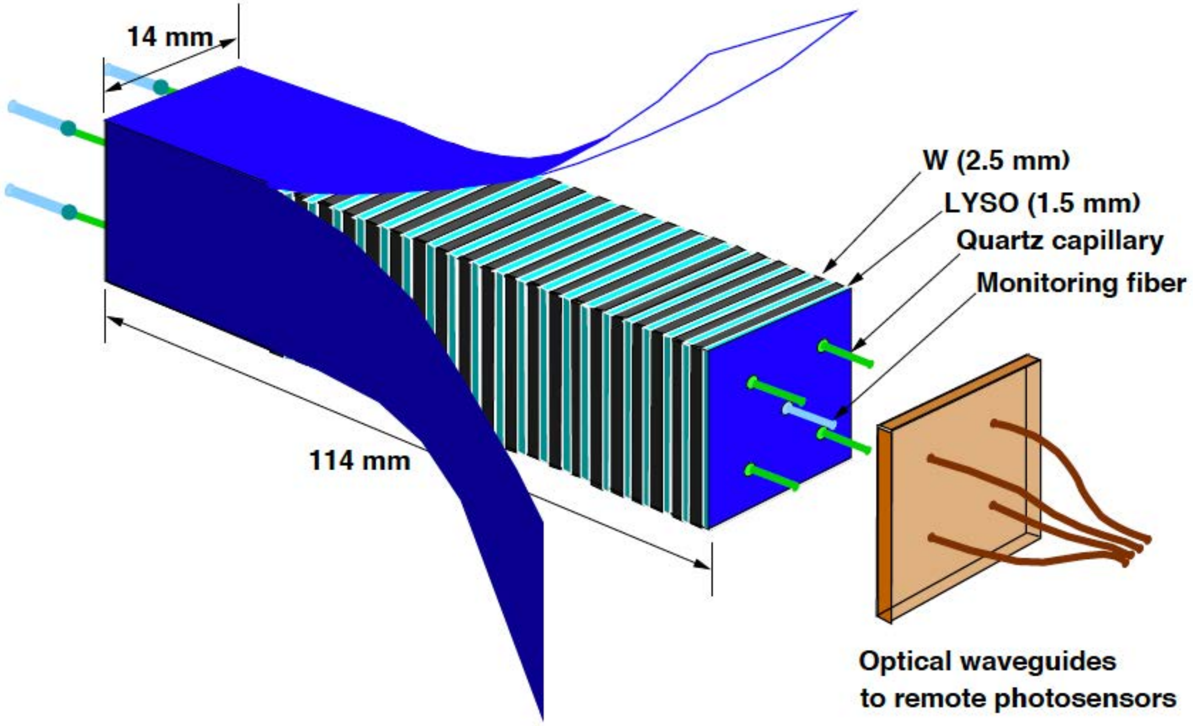


	R_{min}	R_{max}	z coverage	η coverage	Dose	1 MeV n_{eq} fluence
Unit	m	m	m		MGy	$\times 10^{15}$ cm^{-2}
EMB	1.75	2.75	$\|z\| < 5$	$\|\eta\| < 1.67$	0.1	5
EMEC	0.82–0.96	2.7	$5.3 < \|z\| < 6.05$	$1.48 < \|\eta\| < 2.50$	1	30
EMF	0.062–0.065	3.6	$16.5 < \|z\| < 17.15$	$2.26 < \|\eta\| < 6.0$	5000	5000
HB	2.85	4.89	$\|z\| < 4.6$	$\|\eta\| < 1.26$	0.006	0.3
HEB	2.85	4.59	$4.5 < \|z\| < 8.3$	$0.94 < \|\eta\| < 1.81$	0.008	0.3
HEC	0.96-1.32	2.7	$6.05 < \|z\| < 8.3$	$1.59 < \|\eta\| < 2.50$	1	20
HF	0.065–0.077	3.6	$17.15 < \|z\| < 19.5$	$2.29 < \|\eta\| < 6.0$	5000	5000

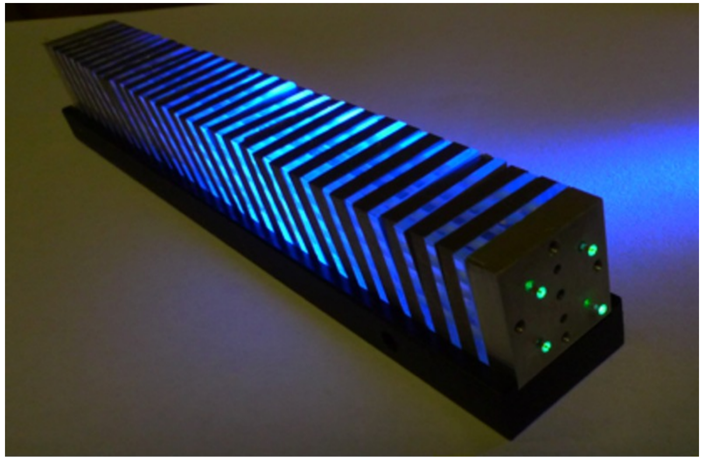
Table 1: Dimensions of the envelopes for the calorimeter sub-systems (including some space for services) and the maximum radiation load at inner radii (total ionising dose is estimated for 30 ab^{-1}). The abbreviations used in the first column are explained in the text.

From
M. Aleksa, et al, Calorimeters for the FCC-hh, CERN-FCC-PHYS-2019-0003, 23 December 2019.

RADiCAL - Ultracompact Sampling EM Calorimetry Modules for beam testing and comparison with simulation.



- Scintillators
  - Crystals
  - Ceramics
- Wavelength Shifters
  - Fluorescent dyes
  - Liquids
  - Ceramics
- Optical Transmission Elements
  - Fiber optics/filaments
  - Capillaries
- Photosensors
  - SiPM
  - GaInP
  - SiC, Diamond, other



Objectives

Energy Resolution: $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.3/E \oplus 0.7\%$ up to $|\eta| < 4$.

Fast response: σ_t = 30-50ps

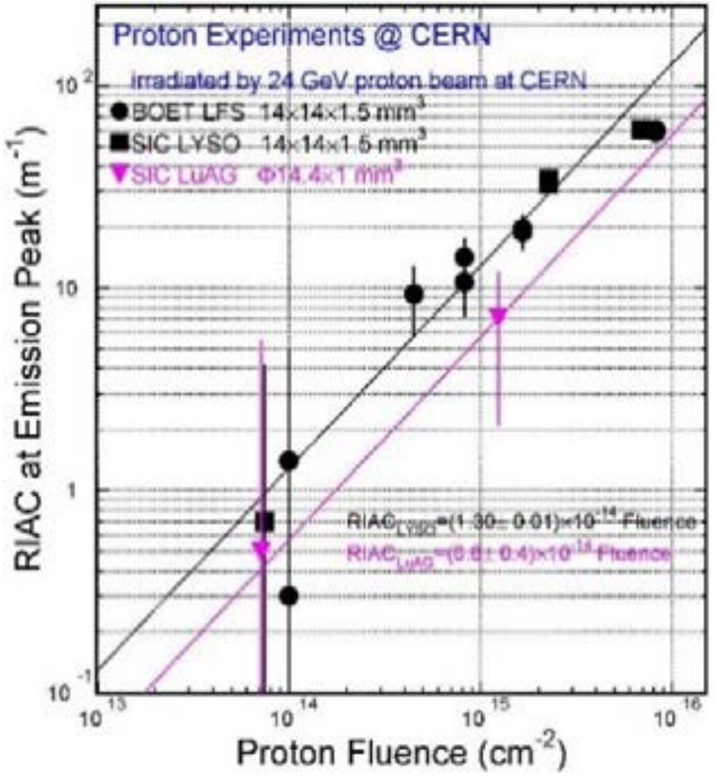
Performant under FCC-hh operating conditions

Fast and Ultrafast Inorganic Scintillators

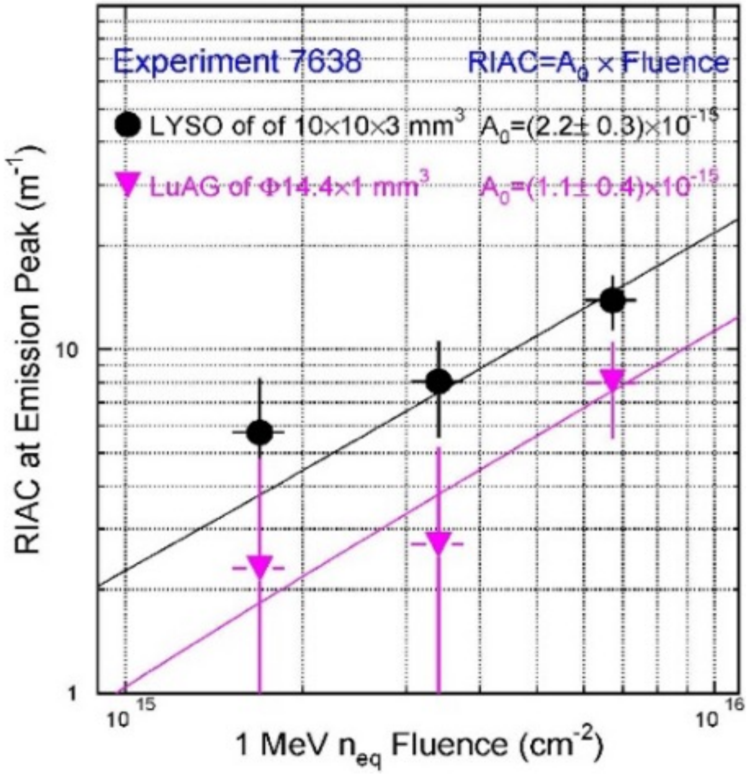
	BaF_2	BaF_2:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	2.77	1.63	1.37	3.10
R_M (cm)	3.1	3.1	2.28	2.4	2.76	2.20	2.07	2.15	2.4	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	22.2	22.4	25.2	20.9	20.9	20.6	22.4	21.5	19.5	27.8
Z_{eff}	51.6	51.6	27.7	31.9	30	28.1	64.8	60.3	31.9	51.8	58.6	33.3
dE/dX (MeV/cm)	6.52	6.52	8.42	8.05	7.01	8.82	9.55	9.22	8.05	8.96	9.82	6.57
λ_{peak}[a] (nm)	300 220	300 220	380	350	350	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.1	1.96	1.87	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	6.6[d]	0.19[d]	0.36[d]	6.5 0.5	100	35[e] 48[e]	9 32	115	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	2,000[d]	57[d]	110[d]	2,100	30,000	25,000[e]	12,000	34,400	10,000	24,000
Decay time[a] (ns)	600 <0.6	600 <0.6	<1	1.5	4	148 6	40	820 50	191 25	800 80	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	610[d]	28[d]	24[d]	43	740	240	391	640	125	318
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.407	0.314	0.439	0.394	0.185	0.251	0.314	0.319	0.214	0.334

December 8, 2019   Presentation by Ren-Yuan Zhu in the 2019 CPAD Workshop at Wisconsin University, Madison, WI

LYSO:Ce and LuAG:Ce Comparison under Irradiation by protons and neutrons

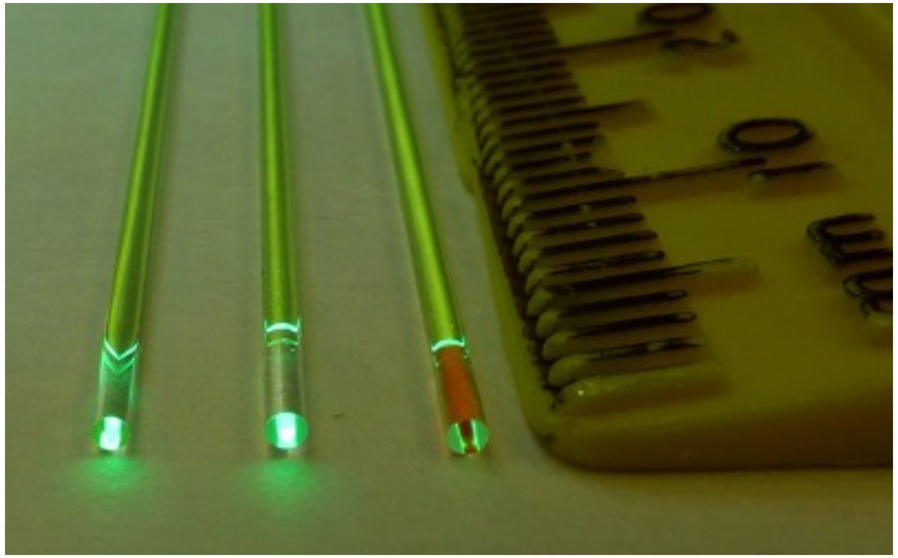


RIAC values as a function of proton fluence for LYSO/LFS crystals and LuAG ceramics irradiated at CERN

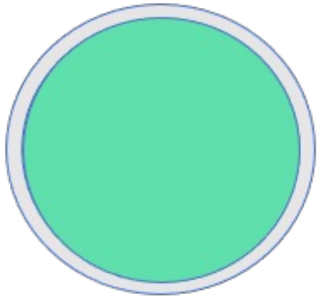


RIAC values as a function of 1 MeV equivalent neutron fluence for LYSO crystals and LuAG ceramics irradiated at LANSCE

New approach to the Fiberoptic Profile

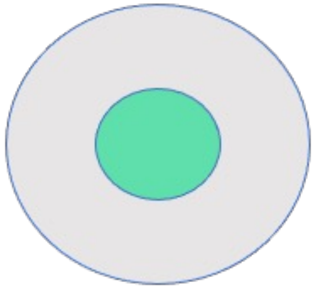


Conventional Optical Fiber



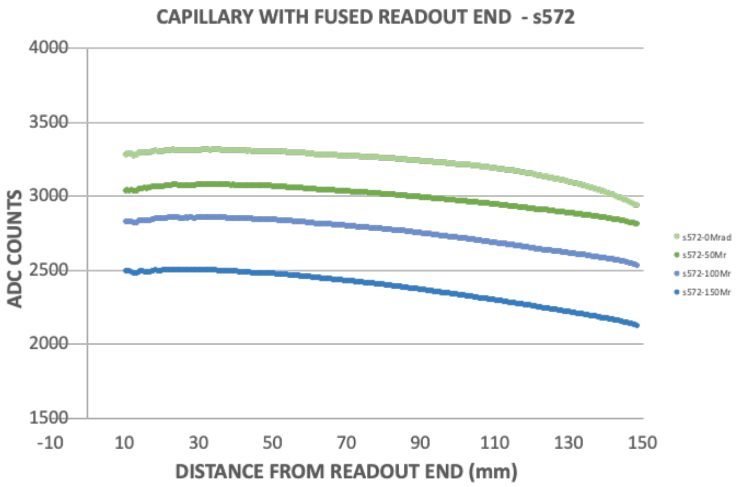
- Optical Path in WLS mediu m is maximal.
- Whole structure – typically polymer - is not rad hard.

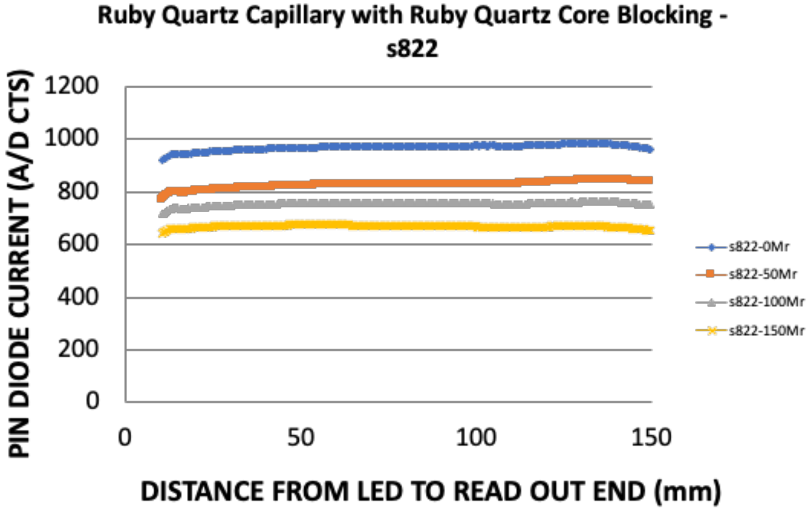
Thick Wall Profile



- Optical Path in WLS medium is significantly reduced.
- High OH^- rad hard Quartz.
- Core liquid is generally more rad hard than polymer.

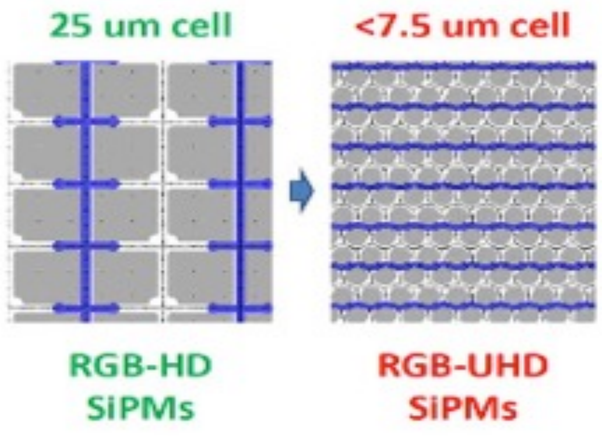
Transmission Studies in capillaries as a function of successive 50Mrad ^{60}Co gamma irradiation doses. ND Rad Lab.



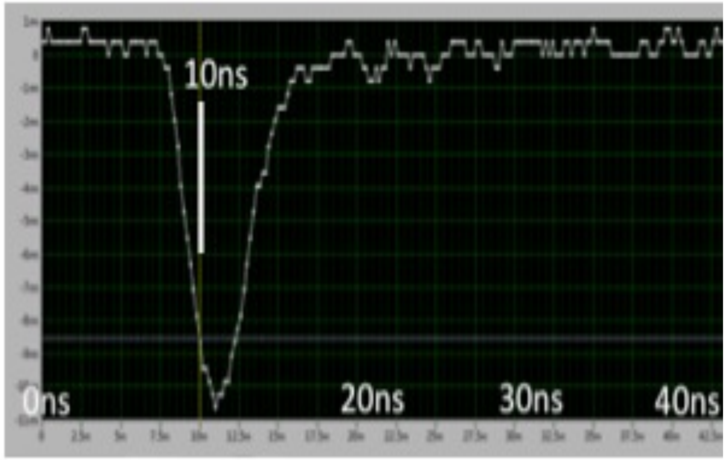


Photosensor Development - SiPM

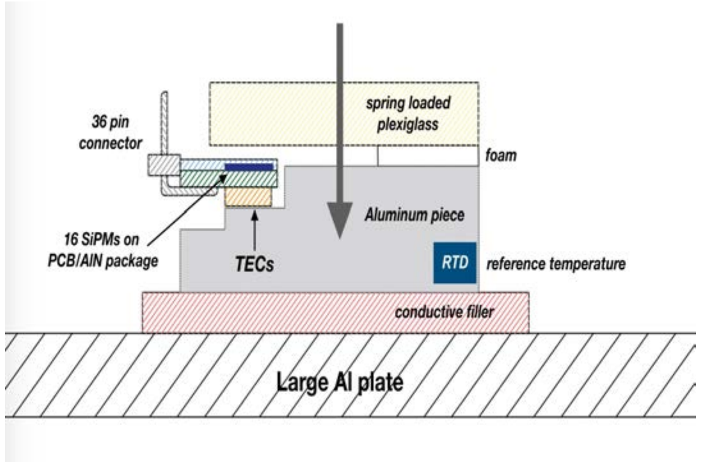
- Pixelated Geiger-mode devices with high photo efficiency across a broad spectral range.
- Intention is to exploit and further the development of localized cooling (TEC) of the SiPM to reduce noise and extend performance lifetime.
- Development of small pixel devices (5-7μm) to enhance efficiency and benefit from fast response time.



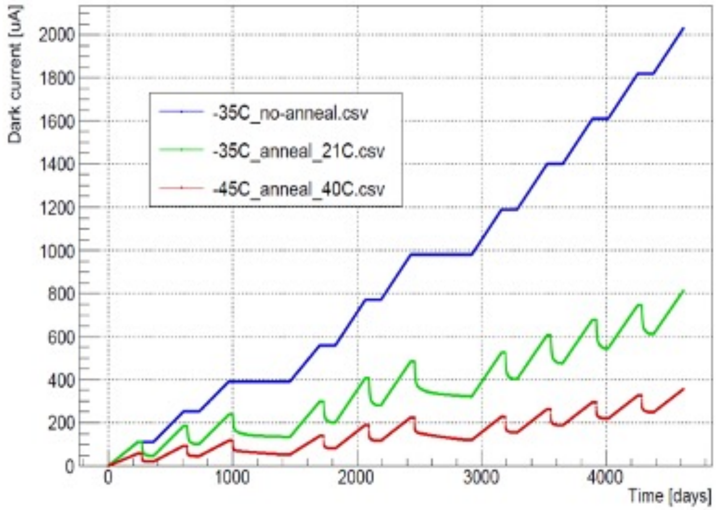
SiPM Development at FBK



Pulse detected from a FBK SiPM with 5μm pixels.



Thermionic Cooling of HPK SiPM (CMS)



Modeled scenario of operation up to 4000fb^{-1} (CMS)

Blue – (-35c operation, no annealing)

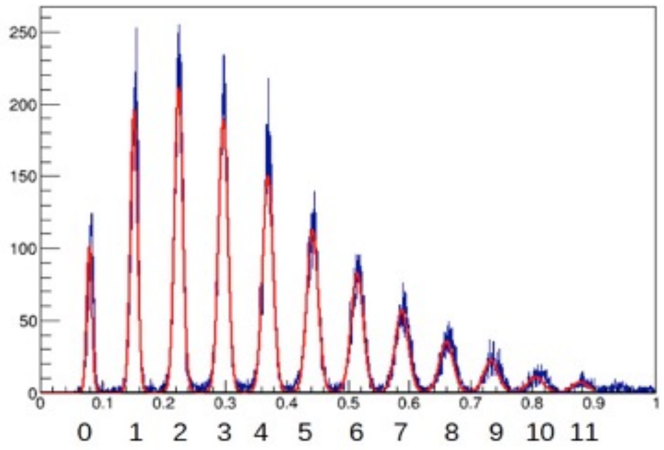
Red – (-45c operation, annealing at 40c)

Photosensor Development – Large Band Gap Devices

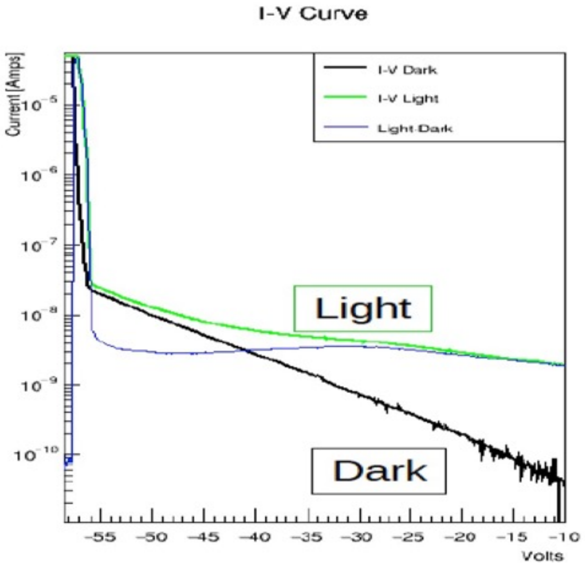
- Larger Band-gap Technologies
  - For operation in very high radiation environments
  - GaInP pixelated devices have been fabricated.
  - Individual photon counting seen, similar to SiPM.
  - Device optimization needed to reduce surface currents seen in the latest version.

  - Challenge here is the lack (currently) of a broad commercial market to help drive development. Pursuing interested industrial partnerships.

Photo of a 4x4 mm^2 GaInP Photosensor consisting of 10 arrays of 0.5 x 1.5mm^2 size and containing 25 μm pixels

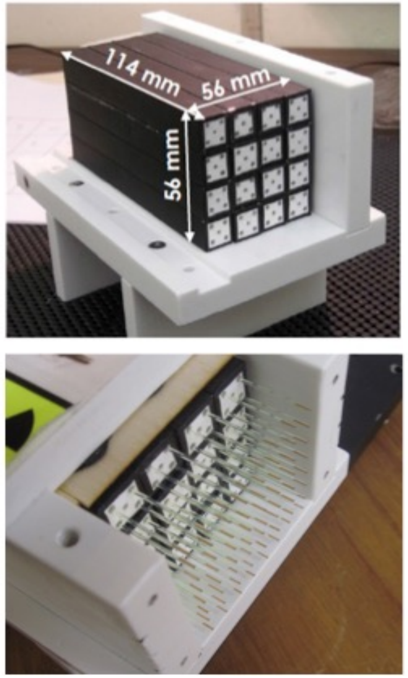


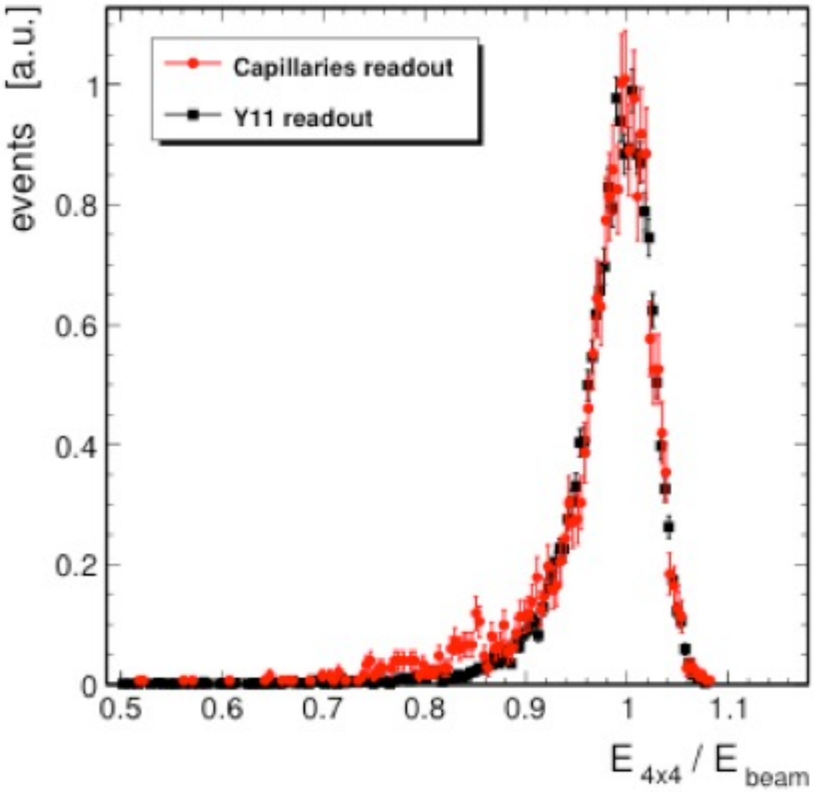
GaInP Photospectrum showing individual photopeaks. Left most (0) is the pedestal. Illumination at λ = 405nm.

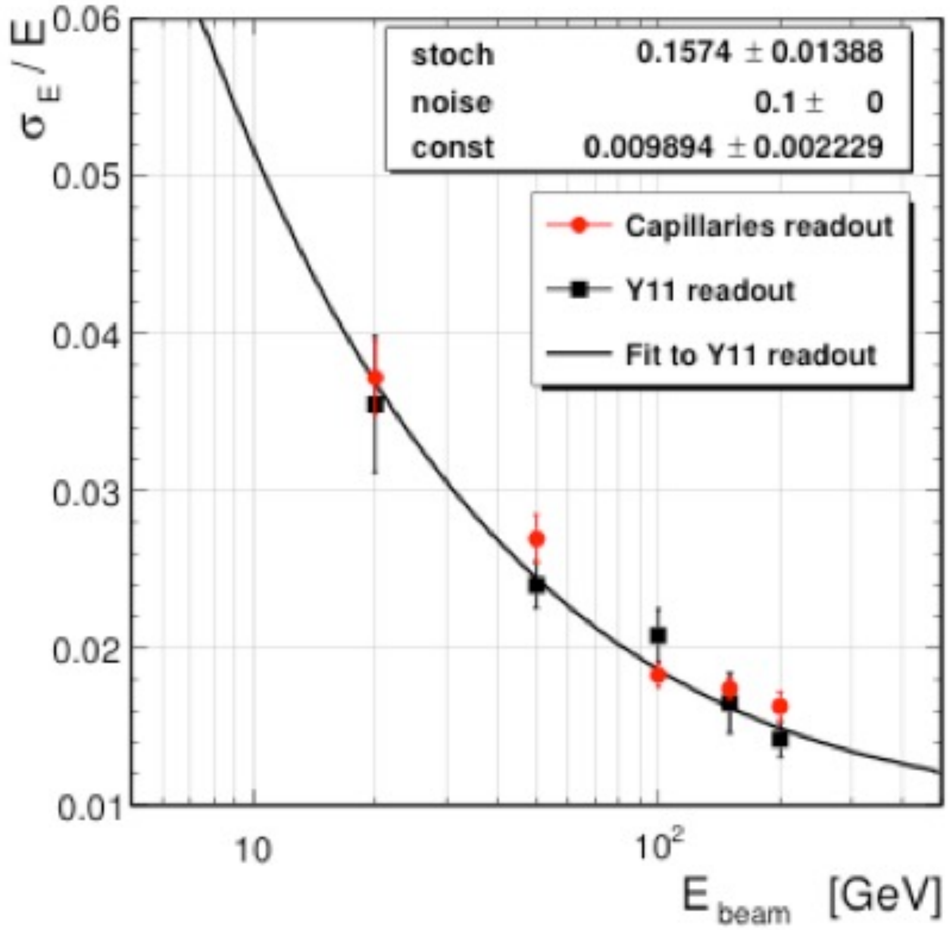


IV curves for GaInP photosensors under illumination and dark field (blue).

Test of a 4x4 array of W/LYSO:Ce with DSB1 WLS - filled Capillaries – CERN H4



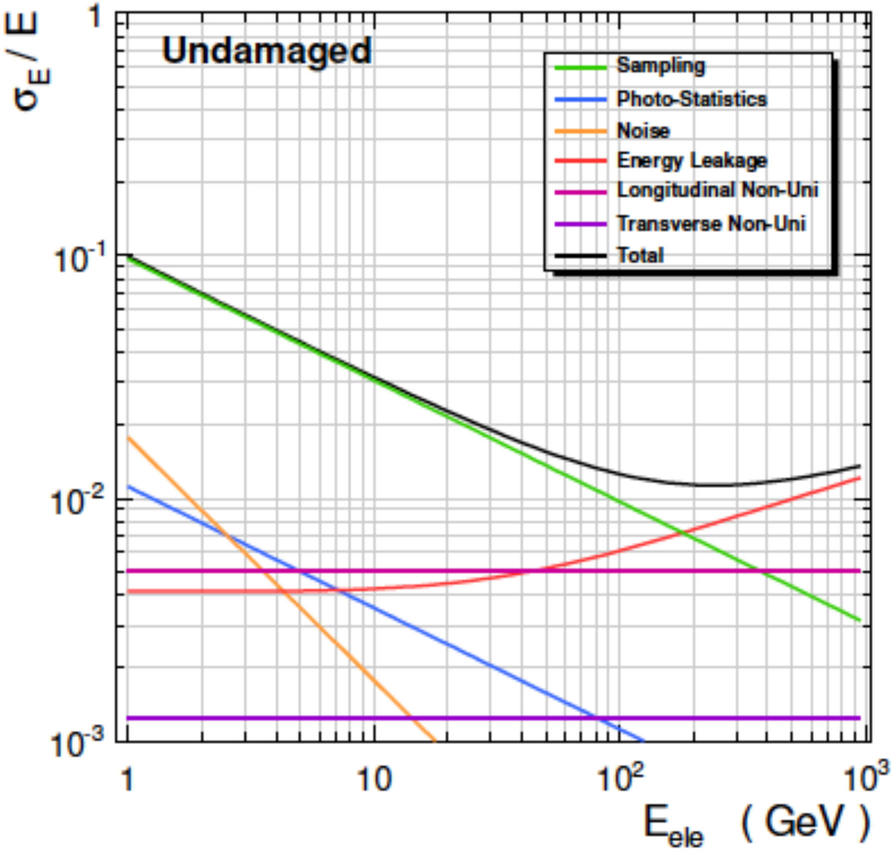


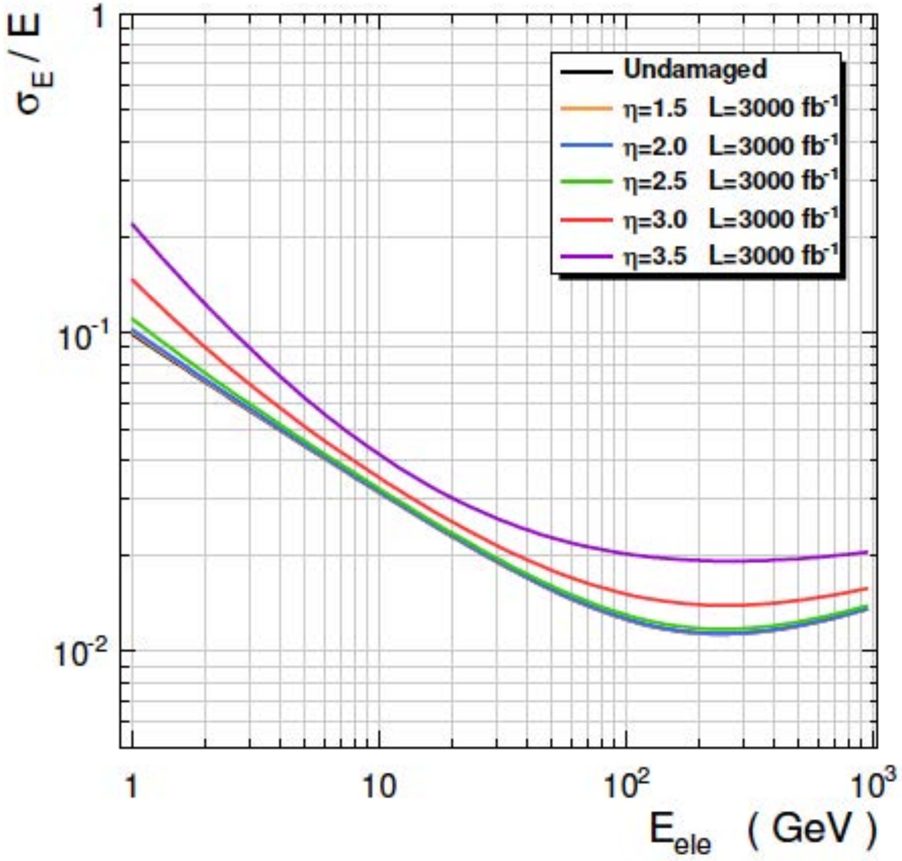


Array tested at CERN H4 with both WLS capillaries and Y11 WLS fibers.

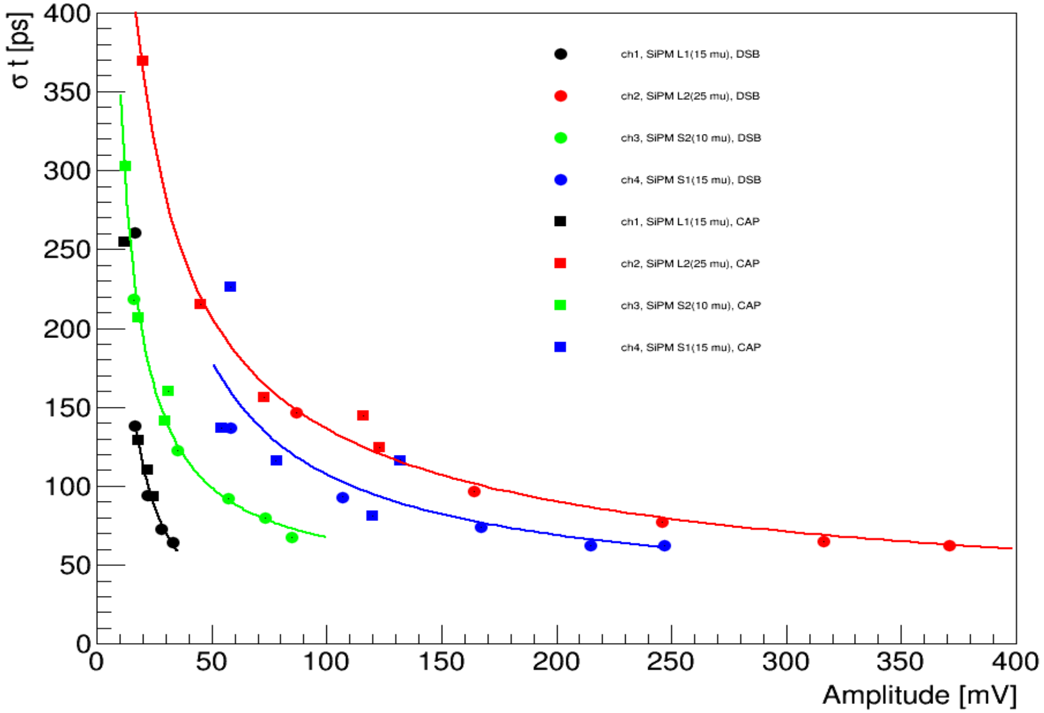
Capillaries with the ruby core blocking

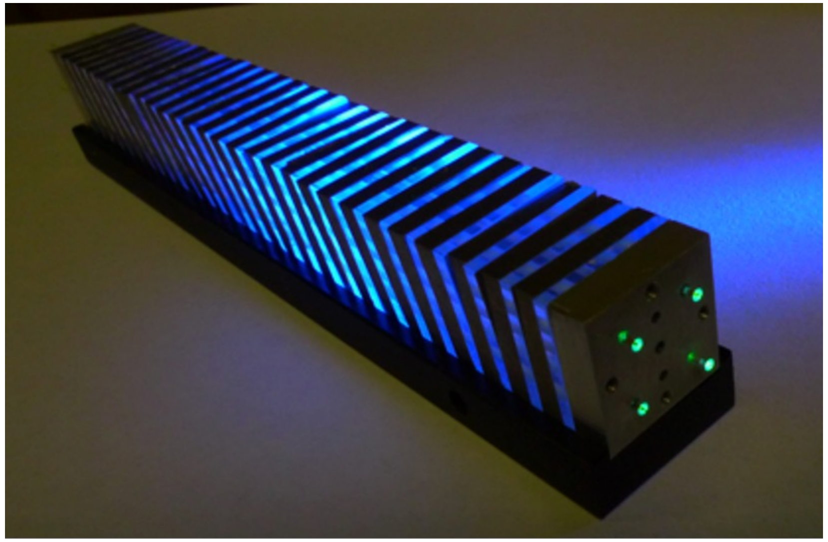
Geant4 Simulation of Energy Resolution (module shown in slide 3).





Preliminary Study of Timing Measurement using W/LYSO:Ce and DSB1 WLS Fibers and Capillaries



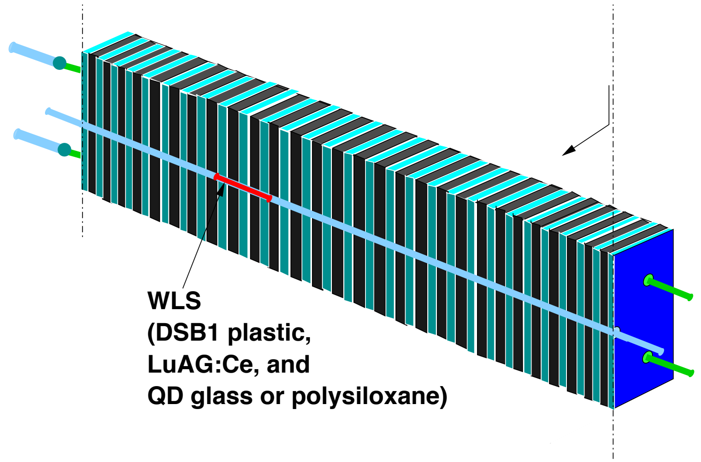


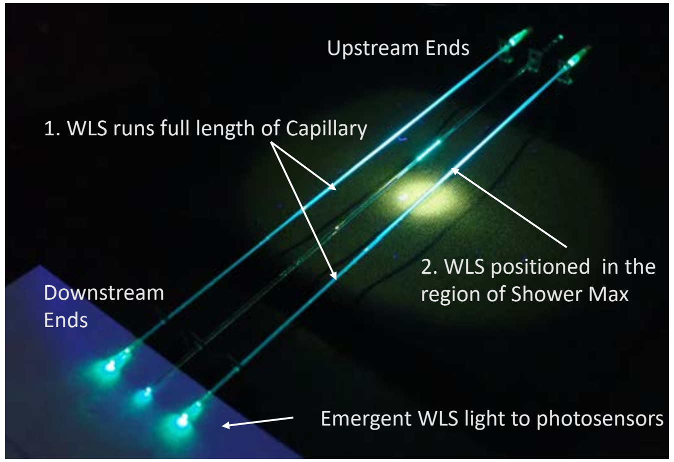
LYSO/W module, single channel time resolution with SiPM readout. Waveshifter readout was either DSB1 WLS dye in a multiclad optical fiber (dots) or DSB1 WLS in a liquid-filled capillary (squares). FTBF, A. Bornheim et al.

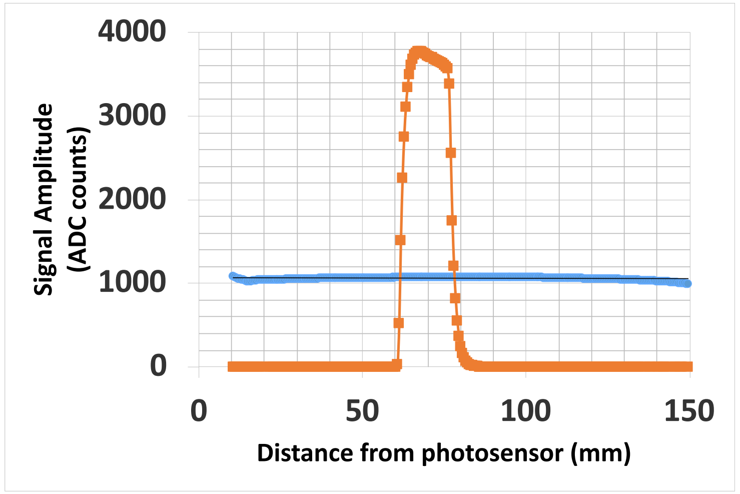
Conclusion and not a surprise: the more light you can collect the better the timing resolution.

Motivates: Capillary use with clear ends rather than ruby quartz ends and read out from both downstream and upstream ends of the capillaries.

New approach to timing measurement with RADiCAL
Timing from WLS at Shower Max.







Specialized WLS Applications

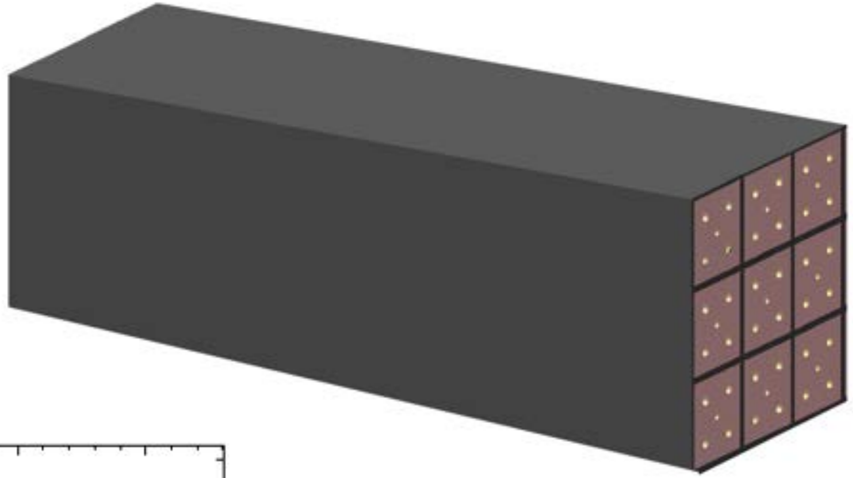
1. To measure shower energy
   WLS runs the full length
2. To measure timing
   WLS filament at Shower Max
   Remainder of capillary is filled with Quartz Fiber and fused solid.
   Capillary can be read out from both ends.

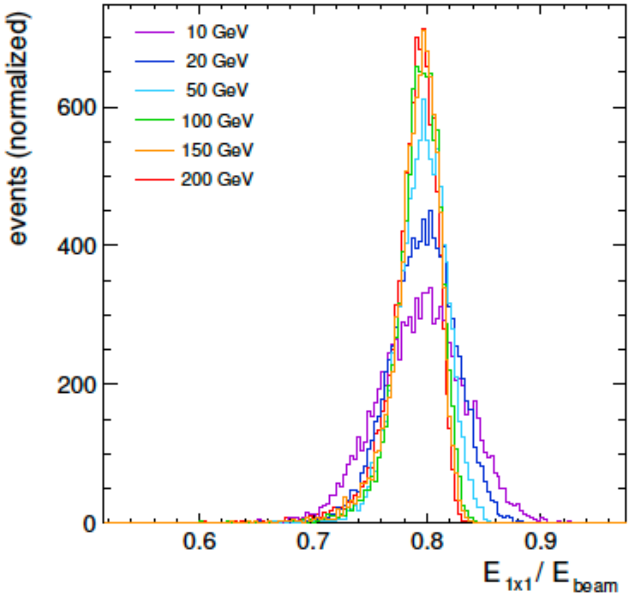
WLS Light Yield as a function of distance from photosensor.

Blue: Energy Capillary
Orange: Timing Capillary

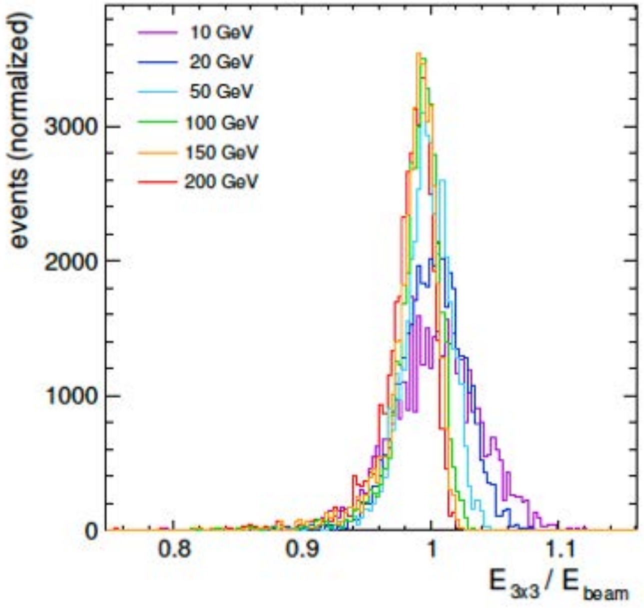
Geant4 Simulation of EM Shower of
50 GeV in a 3x3 array of RADiCAL Modules
14 x 14 x 114 mm^3

Full energy measurement. Shower size set by
Moliere Radius: R_m = 13.7mm



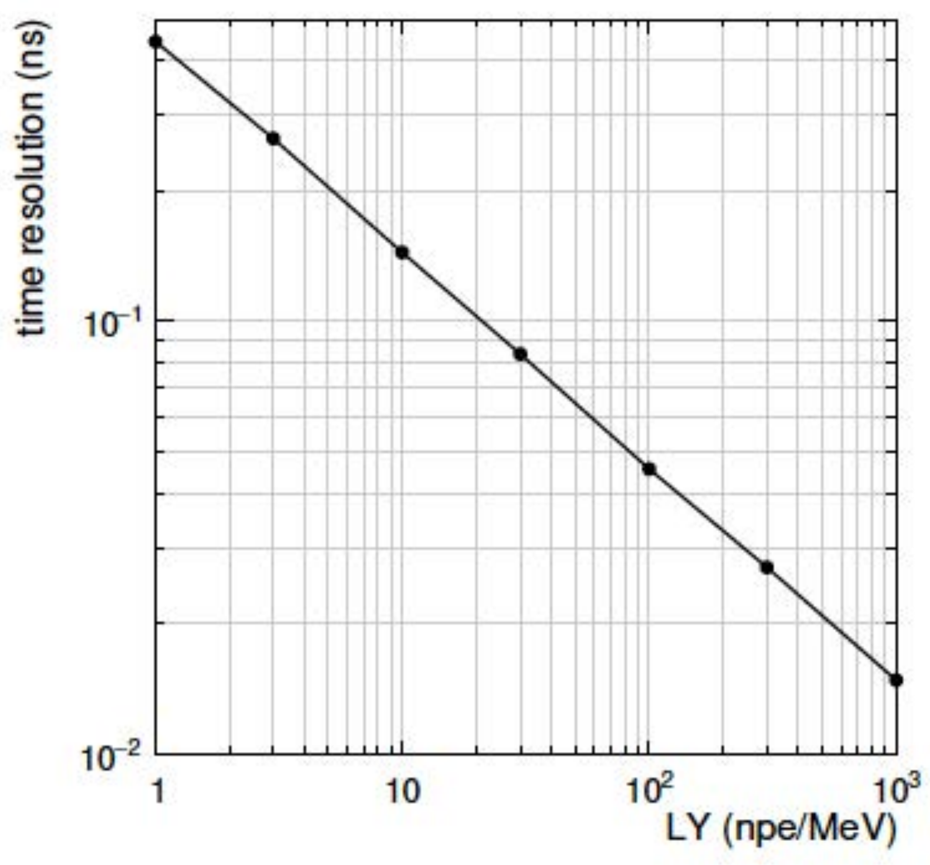


Energy Fraction contained in
Central Module



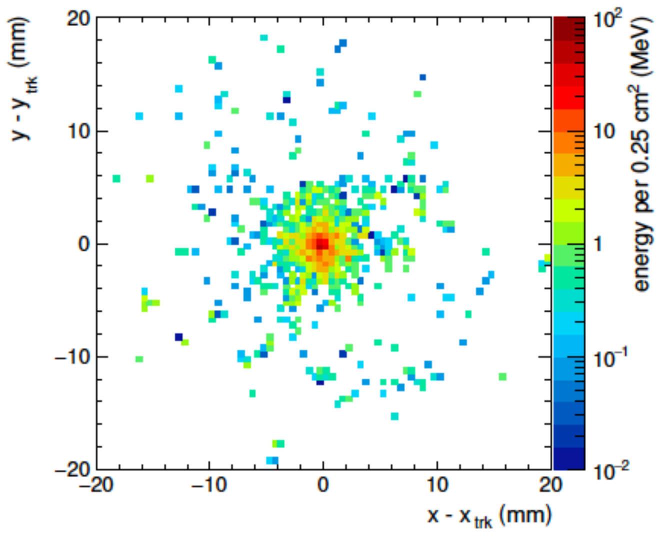
Energy Fraction contained in 3x3 array

Shower Max Timing Simulation with RADICAL



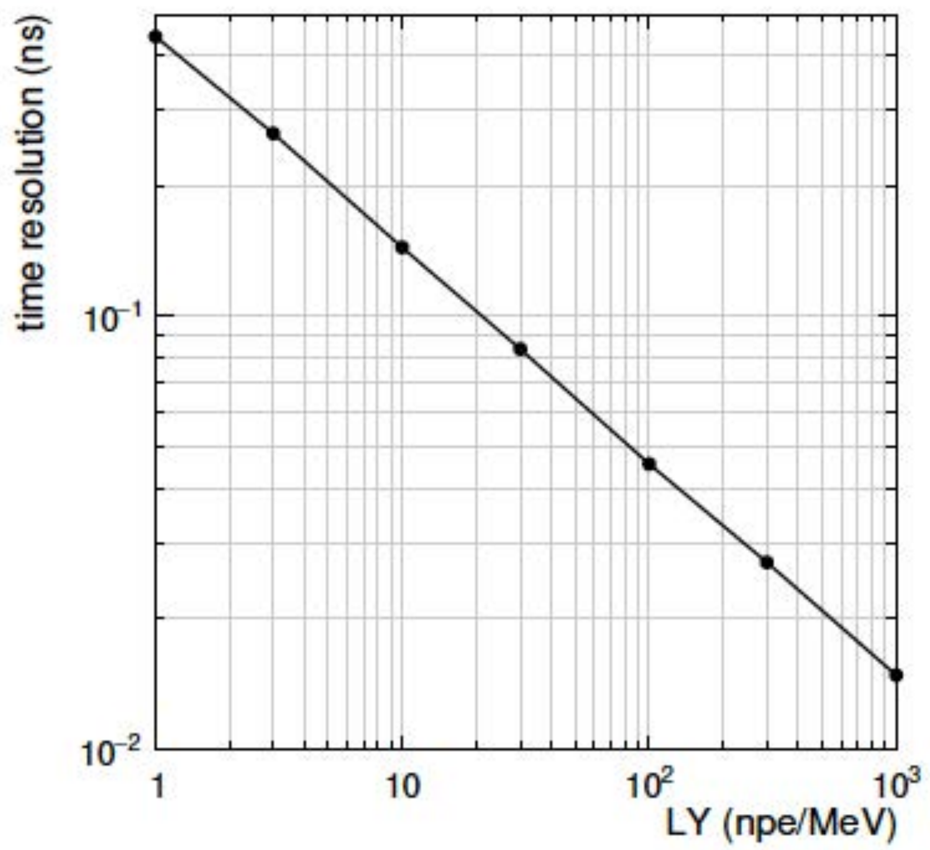
Time resolution vs detected light yield at Shower Max

<u>GEANT4 simulation of the time resolution expected from Shower Max</u>, using LYSO and DSB1 filament. Electrons of 50 GeV Shower size at shower max ~ X_0 = 4.7mm



Profile of the energy at Shower Max
In a LYSO/W Module with WLS filament
at the Shower Max location

Shower Max Timing Simulation with RADICAL



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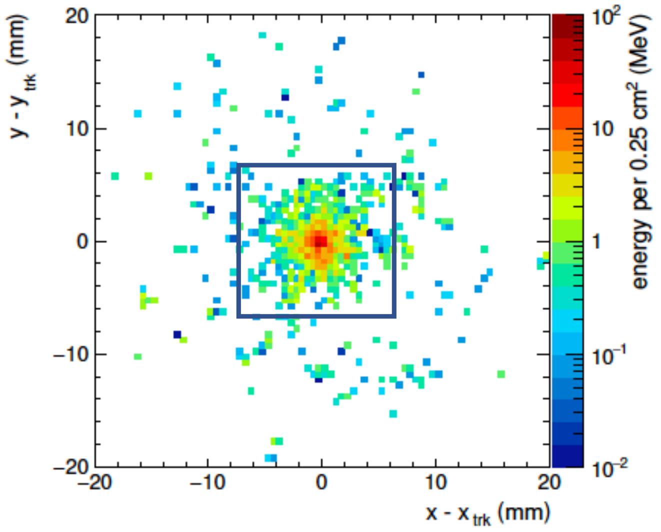


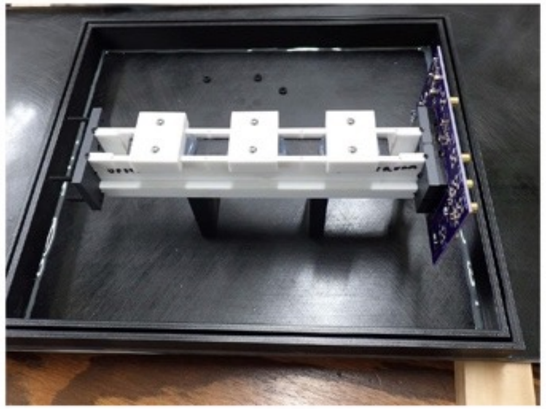
Profile of the energy at Shower Max In a LYSO/W Module with WLS filament at the Shower Max location. Module Cross section imposed…

Testing at Fermilab FTBF

Negative Beam 12 < E < 28 GeV, Positive Beam E =120 GeV

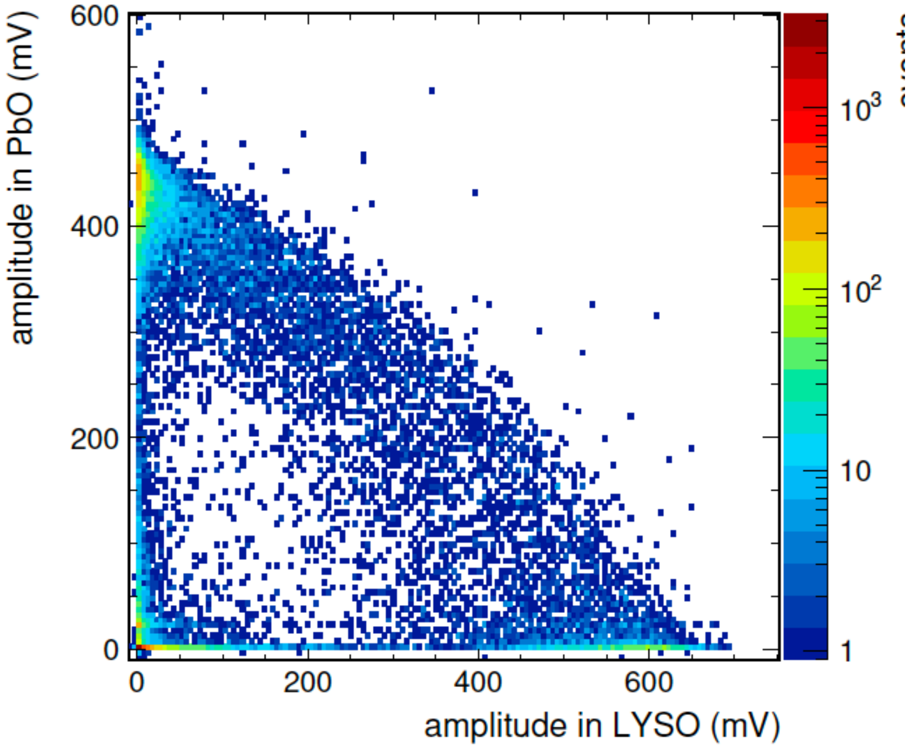
Upstream:
Silicon Tracking
MCP for Timing/Trigger

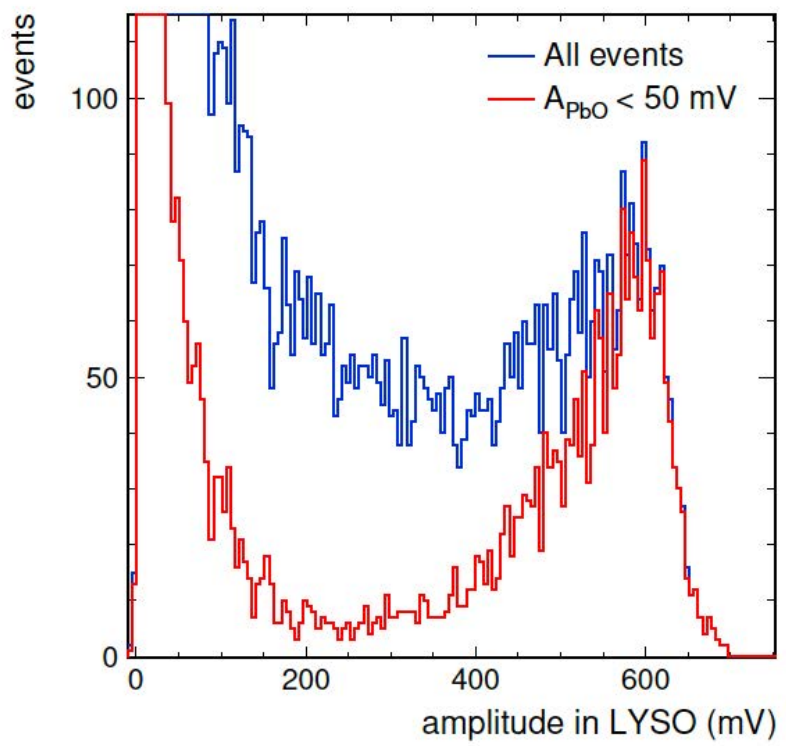
RADiCAL
Module



Downstream:
Pb glass for full EM shower containment.

First Look at Energy signals: Pb glass vs RADiCAL Module No tracking constraint (28 GeV negative beam)





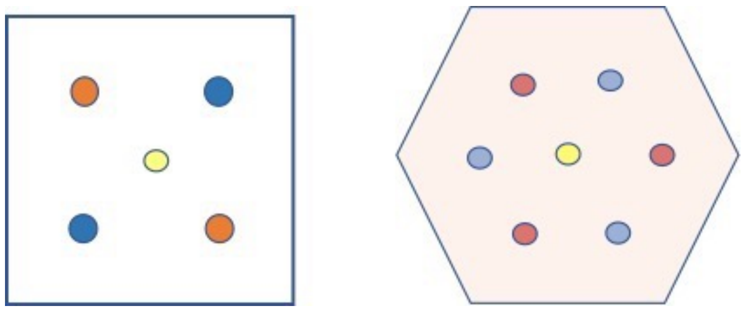
Near term and Future

<u>Near term (June 2022)</u>:

- Time Resolution for:
  - 12< E< 28 GeV negative beam
    - Electrons – silicon tracking constraint
    - “Gammas” – electrons without the tracking constraint
    - MIPs – pions
  - 120 GeV positive beam
    - Protons - Compare timing with BTL modules
- Spatial resolution of EM shower position reconstructed in the RADiCAL module vs incoming beam position from tracking

<u>Future</u>:

- Study of a Hexagonal Modules with simulation
- Advanced Rad-hard Photosensor R&D



Red: Energy Capillary
WLS runs full module depth

Blue: Timing Capillary
WLS at shower max only

Yellow: Calibration
Clear leaky fiber runs full module length for laser light injection

Summary

- RADiCAL R&D to develop highly efficient, ultra-compact and rad hard EM calorimetry elements that are precision timing capable.
- Development and testing of modular elements that can provide:
  1. Energy measurement.
  2. Shower Max timing measurement.
  3. EM Shower Position derived from the region of shower max where the shower cross section is confined within a radiation length.
- Potential applications of the technique or components in other areas:
  - Endcap and Forward Calorimetry
  - Timing detectors
  - Scintillation/WLS detection over compact regions

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