Advanced Optical Instrumentation for Ultra-compact, Radiation Hard Fast-Timing EM Calorimetry

RADiation hard innovative CALorimetry: RADiCAL

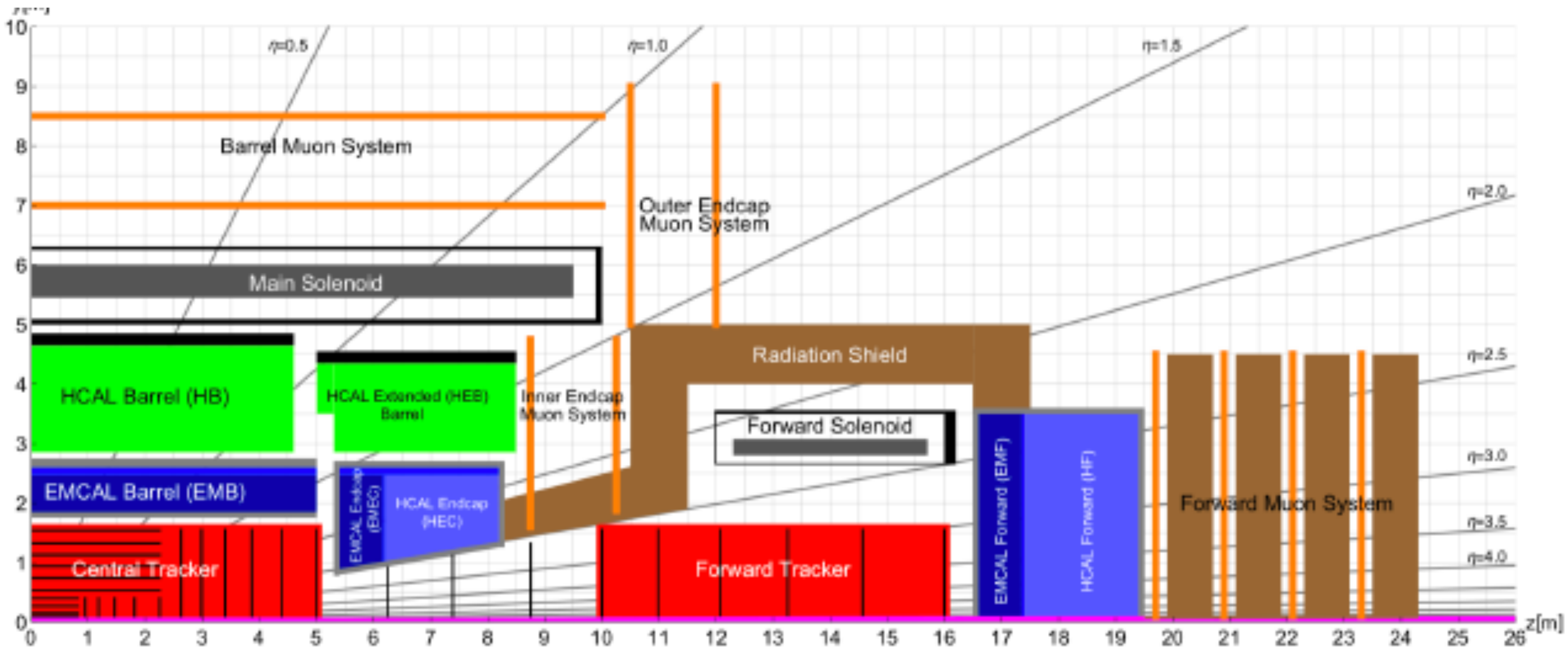
A. Heering, C. Jessop, Yu. Musienko[*], R. Ruchti, M. Vigneault, Y. Wan and M. Wayne,
University of Notre Dame

B. Cox, R. Hirosky, and A. Ledovskoy, University of Virginia

C. Hu, L. Zhang and R-Y. Zhu, California Institute of Technology

Y. Onel, University of Iowa

([*]also at the Institute for Nuclear Research RAS, Moscow, Russia)



	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	$\lvert z\rvert < 5$	$\lvert\eta\rvert < 1.67$	0.1	5
EMEC	0.82–0.96	2.7	$5.3 < \lvert z\rvert < 6.05$	$1.48 < \lvert\eta\rvert < 2.50$	1	30
EMF	0.062–0.065	3.6	$16.5 < \lvert z\rvert < 17.15$	$2.26 < \lvert\eta\rvert < 6.0$	5000	5000
HB	2.85	4.89	$\lvert z\rvert < 4.6$	$\lvert\eta\rvert < 1.26$	0.006	0.3
HEB	2.85	4.59	$4.5 < \lvert z\rvert < 8.3$	$0.94 < \lvert\eta\rvert < 1.81$	0.008	0.3
HEC	0.96-1.32	2.7	$6.05 < \lvert z\rvert < 8.3$	$1.59 < \lvert\eta\rvert < 2.50$	1	20
HF	0.065–0.077	3.6	$17.15 < \lvert z\rvert < 19.5$	$2.29 < \lvert\eta\rvert < 6.0$	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.

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

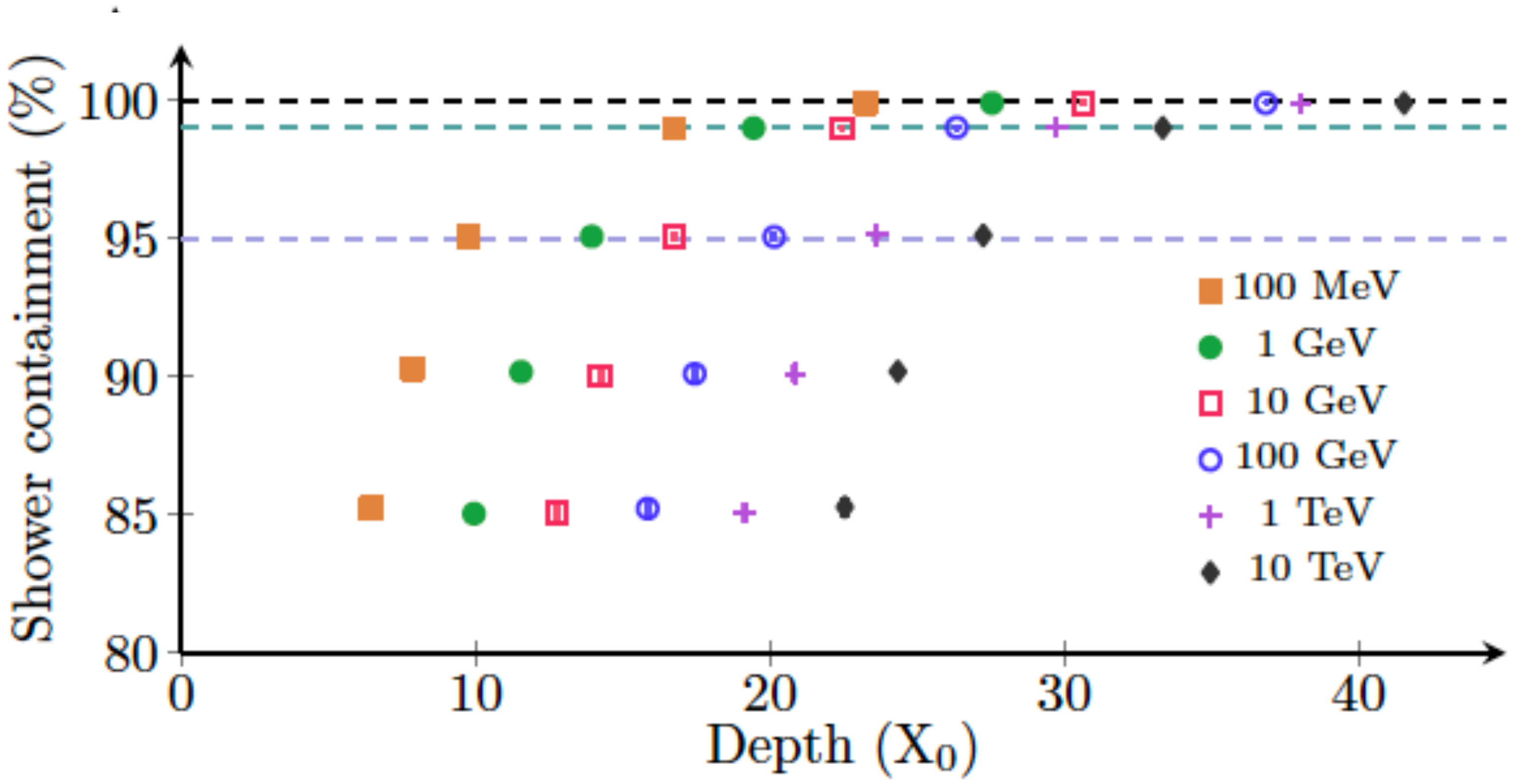


Figure 4: Dependence of the electron shower containment on the calorimeter depth expressed in the radiation lengths. The horizontal lines correspond to the shower containment of 95%, 99% and 100% respectively.

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

RADiCAL - EM Calorimetry

Objectives

Energy Resolution: $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.3/E \oplus 0.7\%$ up to $|\eta| < 4$.
Fast response.
Good performance under FCC-hh operating conditions

Desirable Features

- Very Compact Dimensions
- Excellent energy resolution
- High efficiency
- Fast response (timing capability)
- Triggerability
- Good shower position

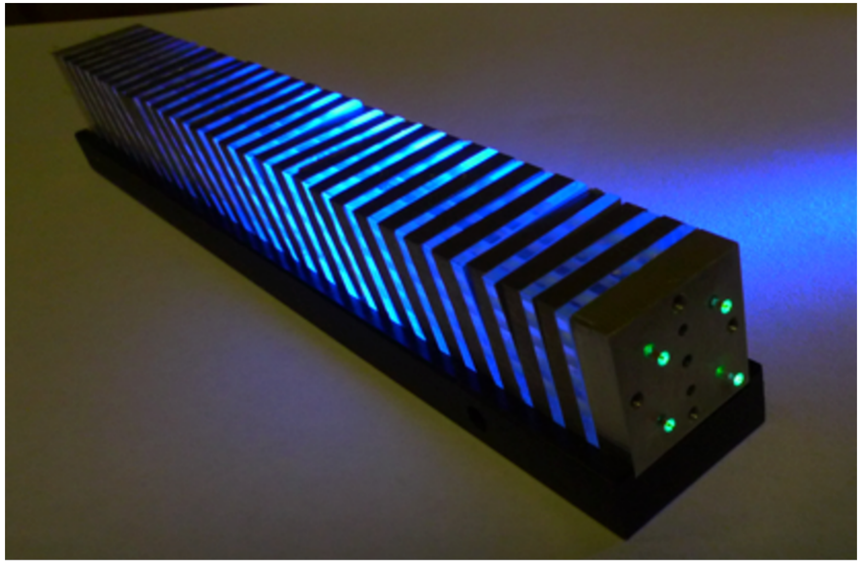
Challenges

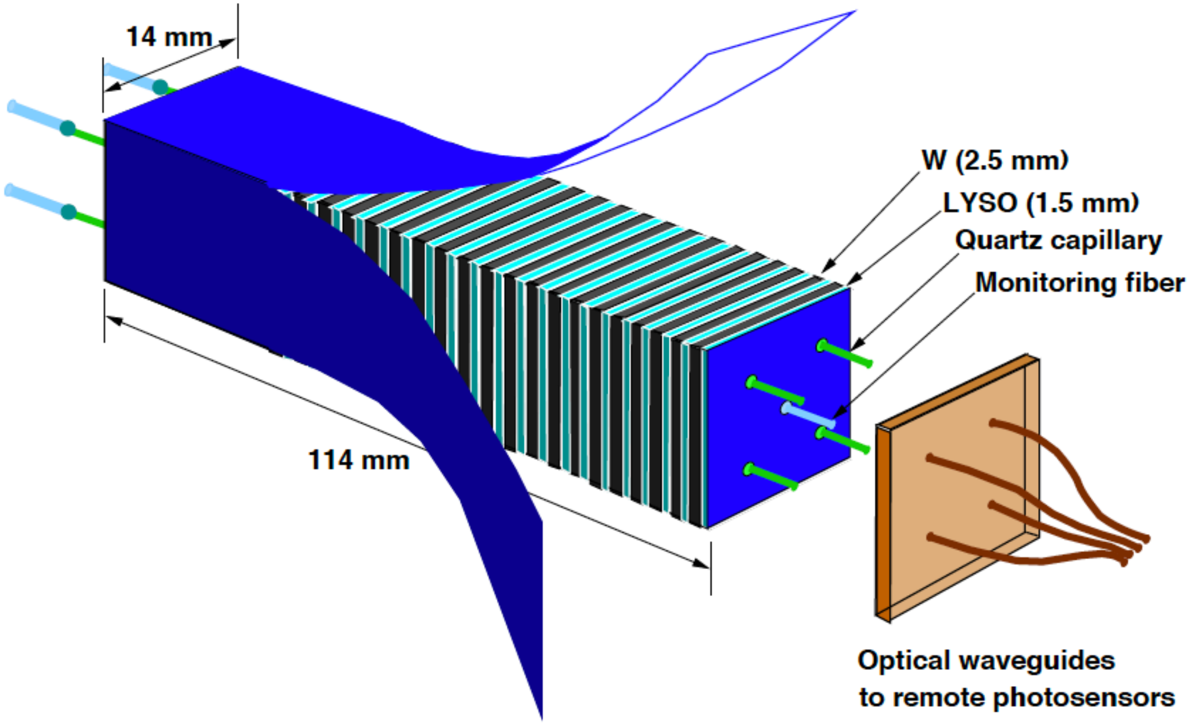
- Radiation Environment
  - Ionization dose
  - Proton fluence
  - Neutron fluence
- Transverse Uniformity
- Longitudinal Uniformity
- Event pileup

RADiCAL Approach

- Ultracompact, Radiation Hard Sampling Calorimetry
- Use of dense materials
  - Small Molière Radius
  - Depth > 25 X_o but < 1 λ
- Optical techniques for fast signal collection
  - HIgh efficiency scintillators and wavelength Shifters
  - Optical paths as short as possible

RADiCAL - Ultracompact Sampling EM Calorimetry Modules for initial beam tests of the technique.





R&D Components of RADiCAL

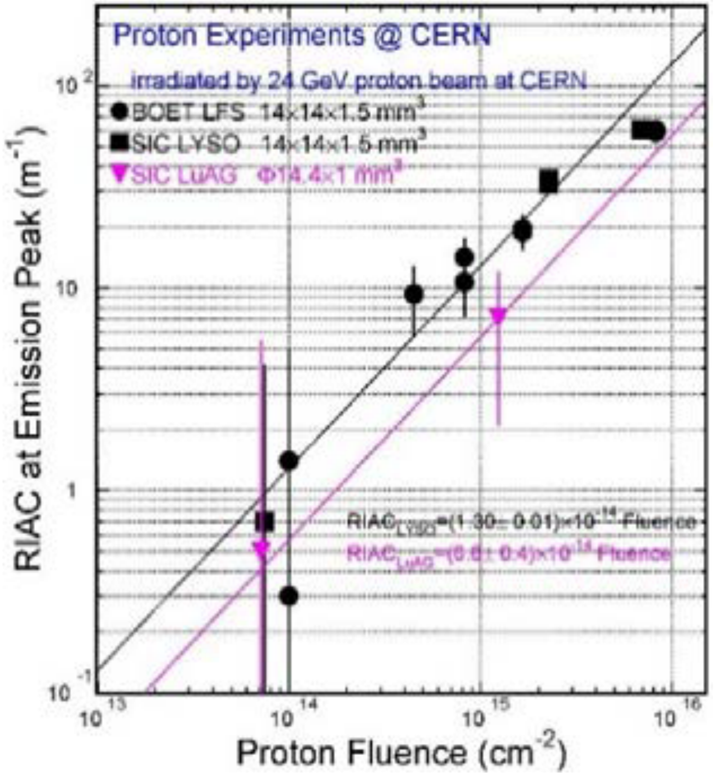
- Scintillators
  - Crystals
  - Ceramics
  - Plastics, glasses
- Wavelength Shifters
  - Fluorescent dyes
  - Liquids
  - Ceramics
  - Quantum Dots
- Optical Transmission Elements
  - Fiber optics
  - Capillaries
- Photosensors
  - SiPM
  - GaInP
- Structures
- Testing
  - Irradiations
  - Beams

Fast and Ultrafast Inorganic Scintillators

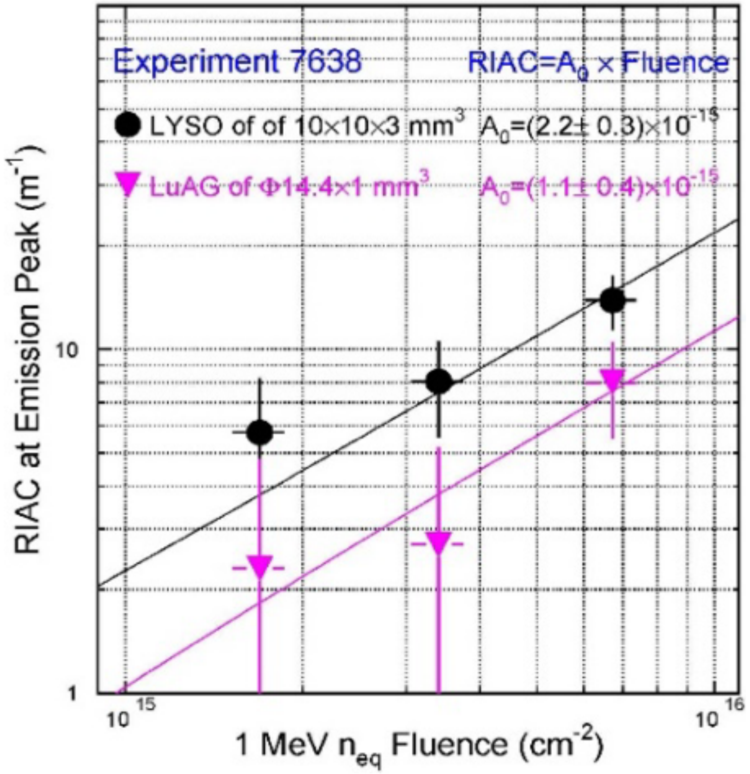
	BaF_2	BaF_2:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	1.14	1.45	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

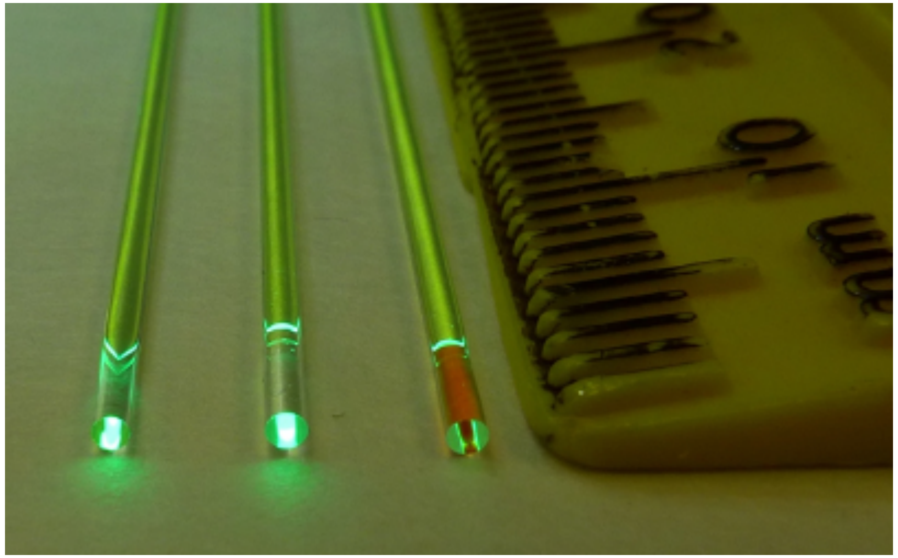


RIAC values as a function of 1 MeV equivalent neutron fluence for LYSO crystals and LuAG ceramics irradiated at LANSCE

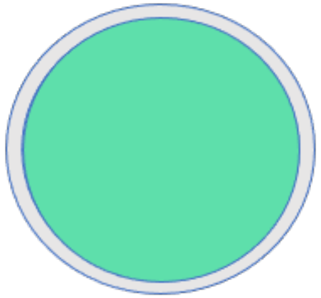
Scintillation materials under investigation include:

1. Inorganic scintillation crystals and ceramics are the preferred approach because of material density and light efficiency.
   - LYSO, LuAG, GGAG, GYAG, GLuAG…
   - Ce 3+, Pr 3+ doping and also Ca co-doping.
   - Rad hardness of LYSO studied up to 300Mrad ionization dose and neutrons up to 9 x 10^{15} n_{eq}/cm^2 and protons up to 8 x 10^{15} p/cm^2.
   - Currently LYSO+SiPM are the key elements of the CMS BTL.
2. Some novel scintillating ceramics such as LuAG:Ce have greater radiation hardness than LYSO.

New vision of the Fiberoptic Profile

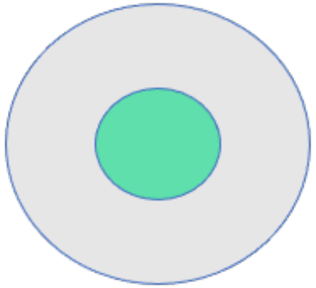


Conventional Optical Fiber



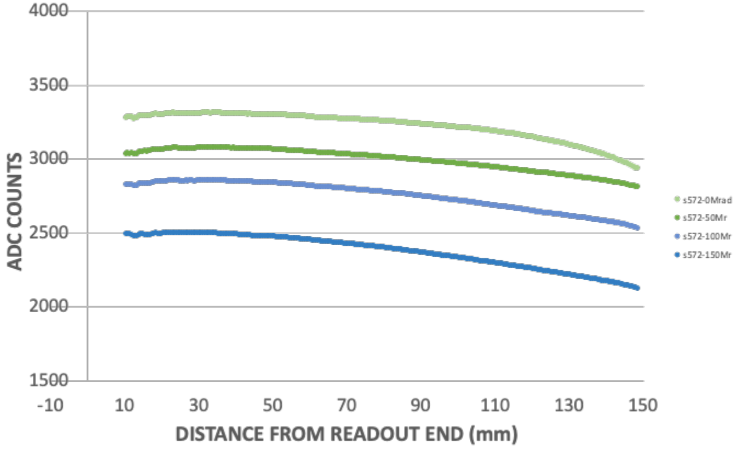
- Optical Path in WLS mediu m is maximal.
- Whole structure – typically polymer - is not rad hard.

Thick Wall Profile

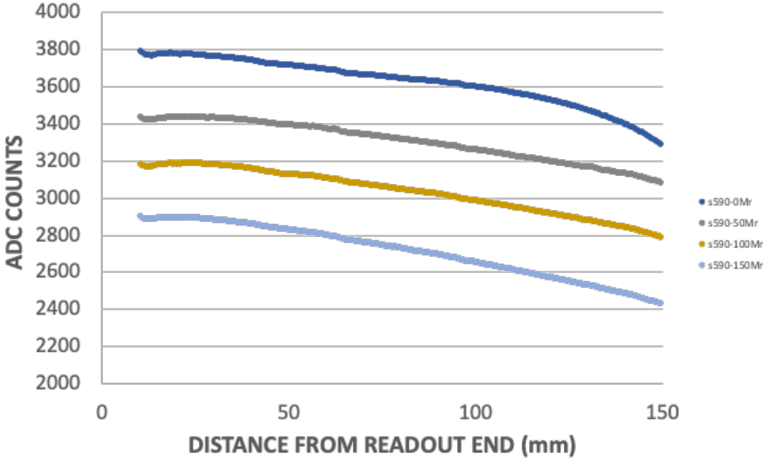


- Optical Path in WLS medium is significantly reduced.
- High OH- rad hard Quartz.
- Core liquid is generally more rad hard than polymer.

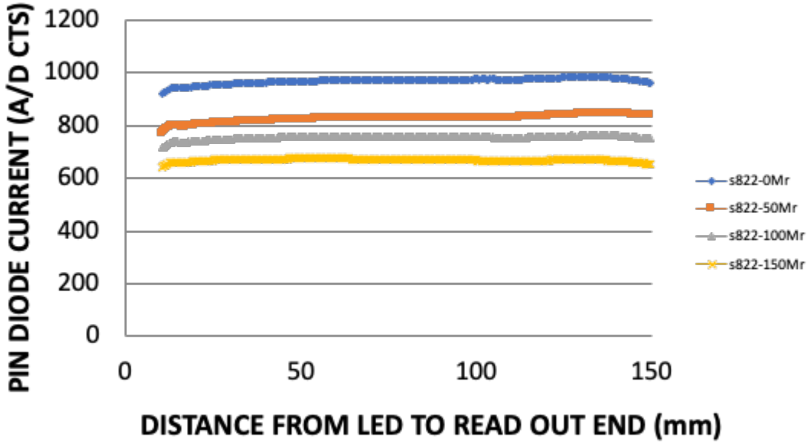
CAPILLARY WITH FUSED READOUT END - s572



CAPILLARY WITH CLEAR QUARTZ INSERT AT READOUT END - S590



Ruby Quartz Capillary with Ruby Quartz Core Blocking - s822

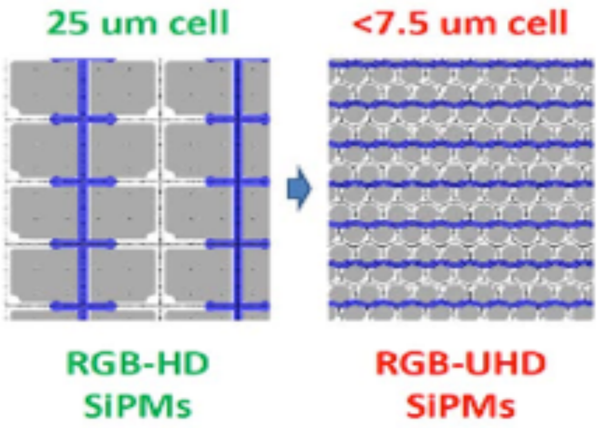


Transmission Studies in capillaries as a function of successive 50Mrad ^{60}Co gamma irradiation doses. ND Rad Lab.

Wavelength shifters and optical transmission elements under investigation…

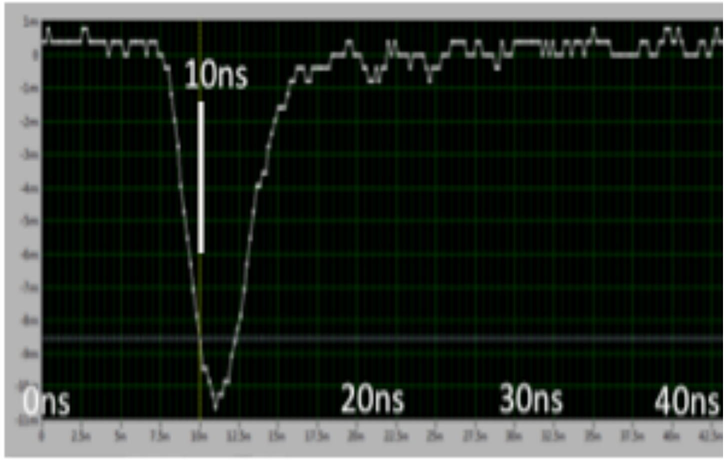
- If photosensors cannot be positioned proximately to the scintillator, efficient and fast waveshifting of the scintillation light and light transfer to remotely placed photosensors are needed.
- WLS materials specialized to different scintillators
  - To shift 420-425nm to 490-500nm, WLS dyes DSB1 and DSF1
  - To shift 350-380nm to 530-560nm, WLS dyes based on new hydroxyflavones
  - Quantum Dot/siloxane and glass composites to shift longer wavelengths
- Optical transmission elements
  - Capillaries – sealed and liquid WLS filled quartz structures
    - Studied to 250Mrad ionization dose and up to 10^{15} p/cm^2.
  - Capillaries filled with inorganic, solid WLS materials
  - Quartz fibers
  - Novel optical transmission structures

Photosensor Development - SiPM

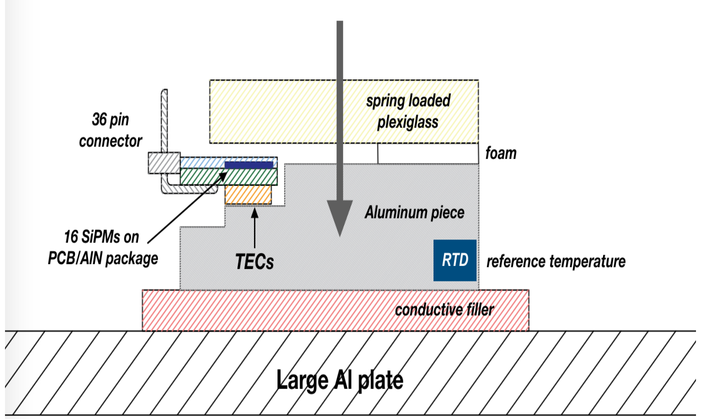


[FBK SiPM

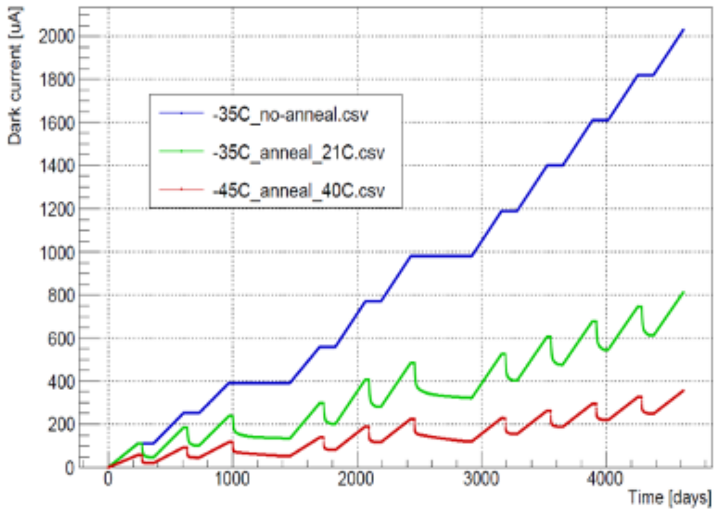
- Pixelated Geiger-mode devices with high photo efficiency across a broad spectral range.
- Particularly effective for longer wavelength light detection.
- Already impactful for light detection of:
  - CMS BTL - LYSO emission (420nm)
  - CMS HCAL - Y11 emission (500nm)
  - In our R&D DSB1 emission (490nm), LuAG:Ce emission (520nm) and hydroxyflavone emissions (530-560n
- Intention is to exploit and further the development of localized cooling (TEC) of the SiPM to reduce noise and extend performance lifetime.
- Continue the development of small pixel devices (5-7μm) to enhance efficiency and benefit from fast response time.



Pulse detected from a FBK SiPM with 5μm pixels.



Thermionic Cooling of HPK SiPM



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

Blue – (-35c operation, no annealing)

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

Photosensor Development – Large Band Gap Devices

- Larger Band-gap Technologies
  - Hold promise for operation in very high radiation environments, but it is still rather early days in this R&D in spite of several device versions produced.
  - 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. Seeking interested industrial partnerships.

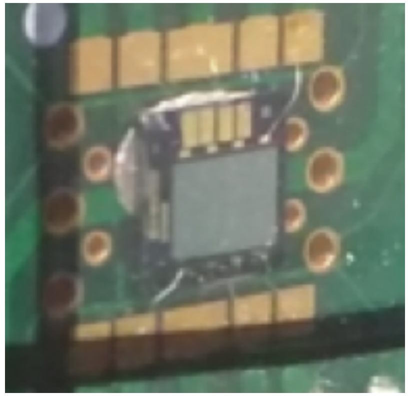
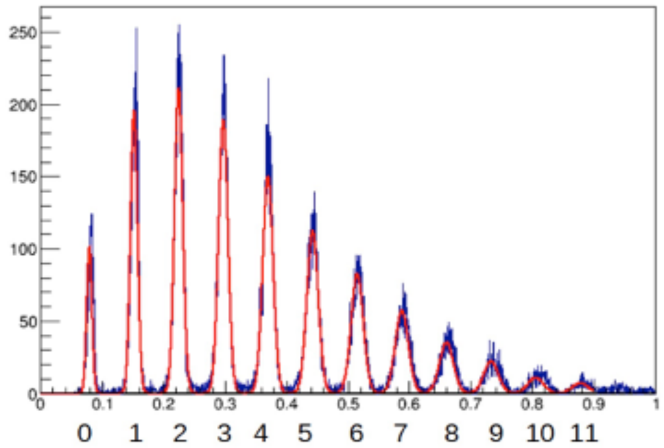
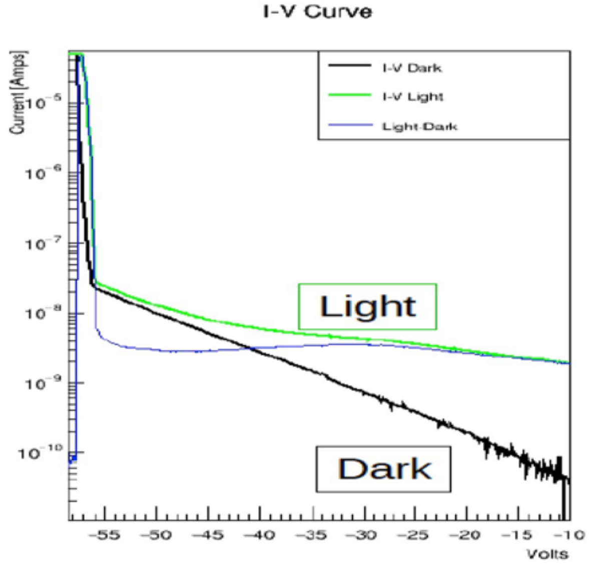


Photo of a 4x4 mm^2 GaInP Photosensor consisting of 10 arrays of 0.5 x 1.5mm^2 size and containing 25 μm pixels

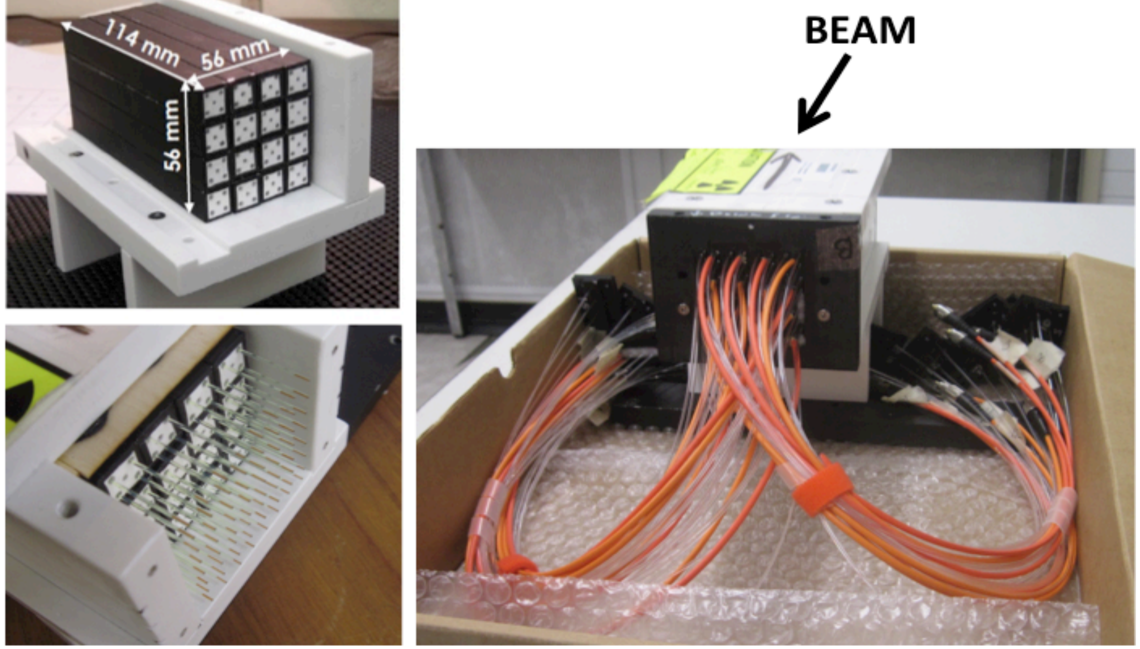


GaInP Photospectrum showing individual photopeaks. Left most (0) is the pedestal. Illumination at λ = 405nm.



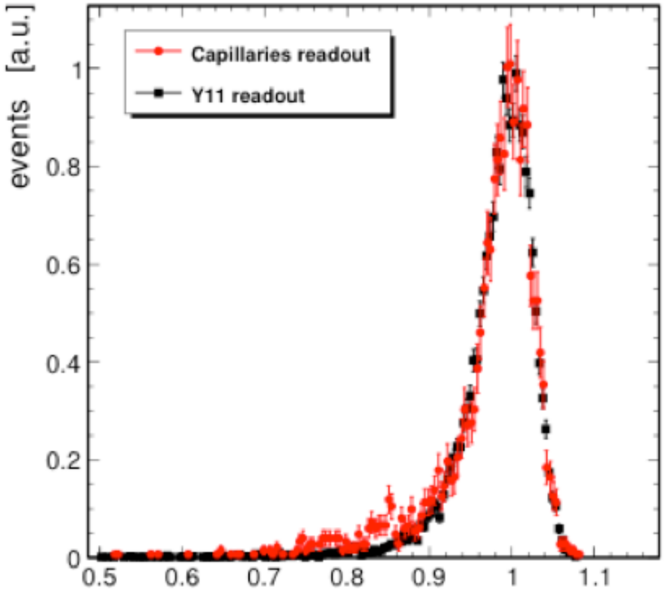
IV curves for GaInP photosensors under illumination and dark field (blue).

Test of a 4x4 array of W/LYSO:Ce with DSB1 WLS Capillaries

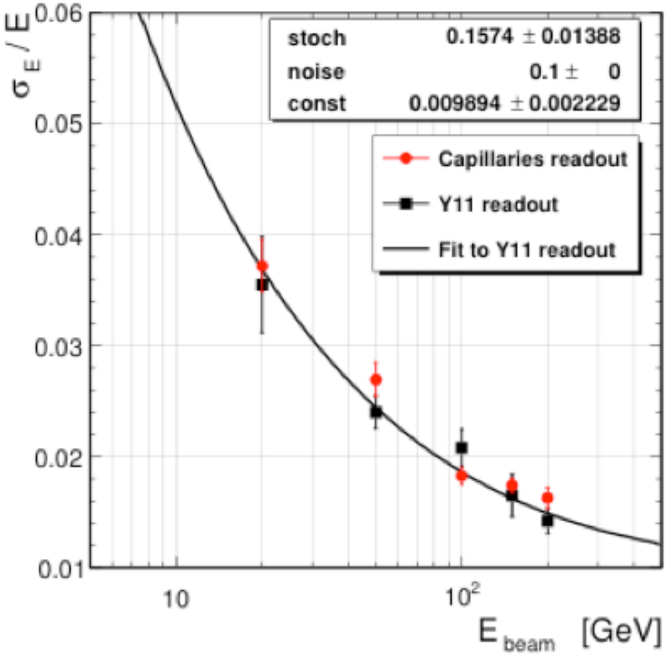


Array tested at CERN H4 with both WLS capillaries and Y11 WLS fibers.

Capillaries with the ruby core blocking

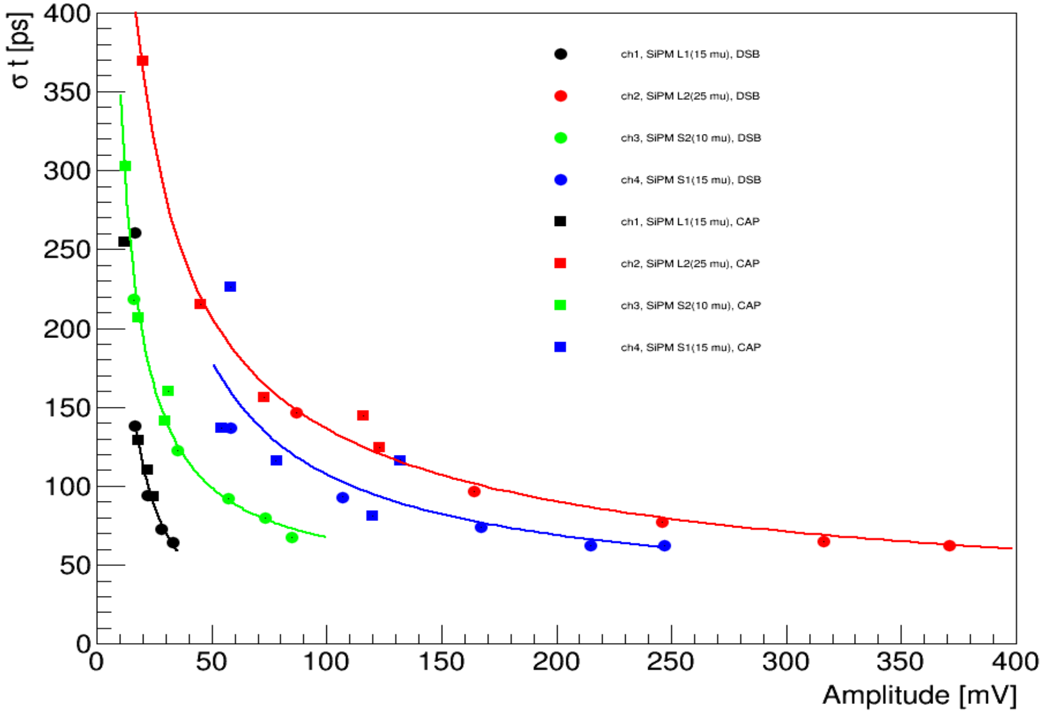


Measured 4x4 energy compared to the beam energy for 100 GeV electrons. CERN H4

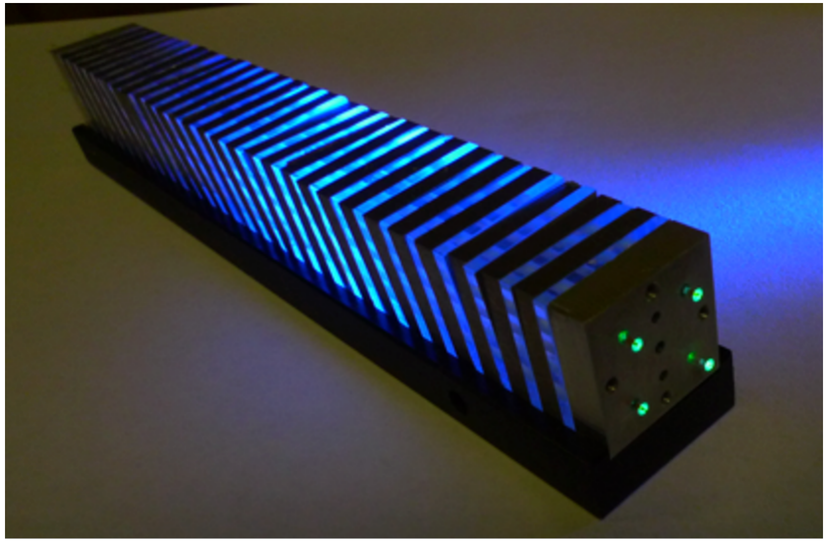


Energy resolution vs electron beam energy CERN H4.

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



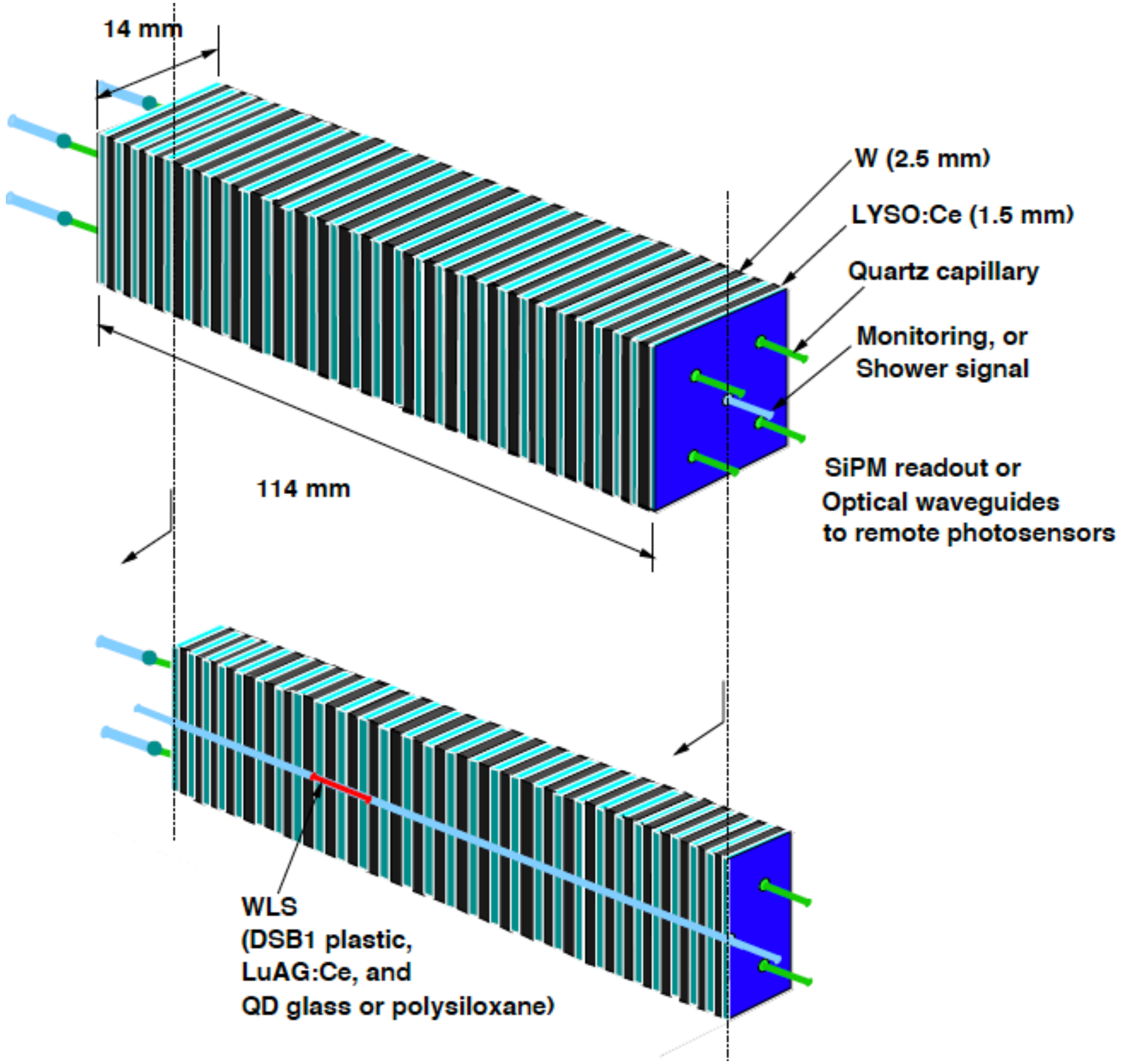
LYSO/W module, single channel time resolution with SiPM readout.   Waveshifter readout was either DSB1 WLS dye in a multiclad optical fiber (dots) or DSB1 WLS in a liquid-filled capillary (squares). Fermilab Test Beam, A. Bornheim et al.



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

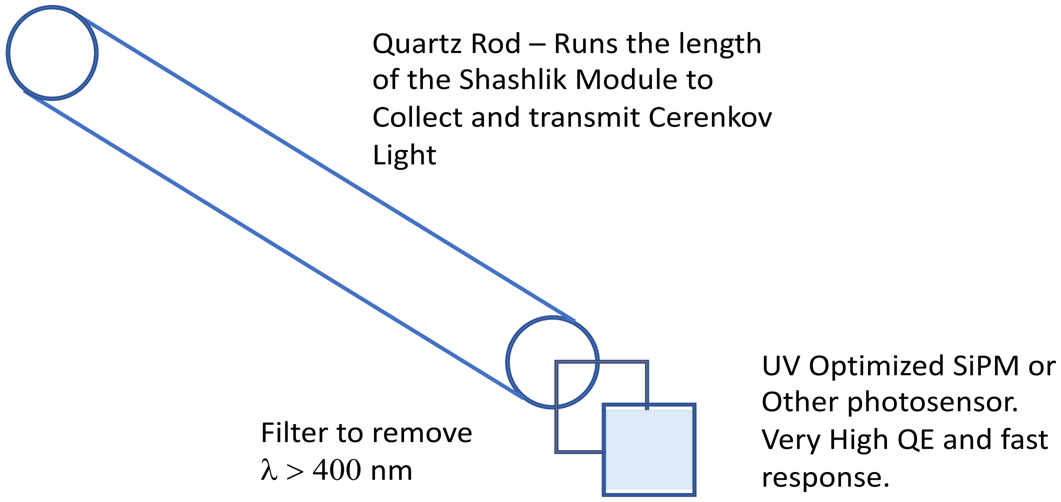
Motivates: Capillary use with clear ends rather than ruby quartz ends and read out from both downstream and upstream ends of the capillaries.

New approach to timing measurement with RADiCAL

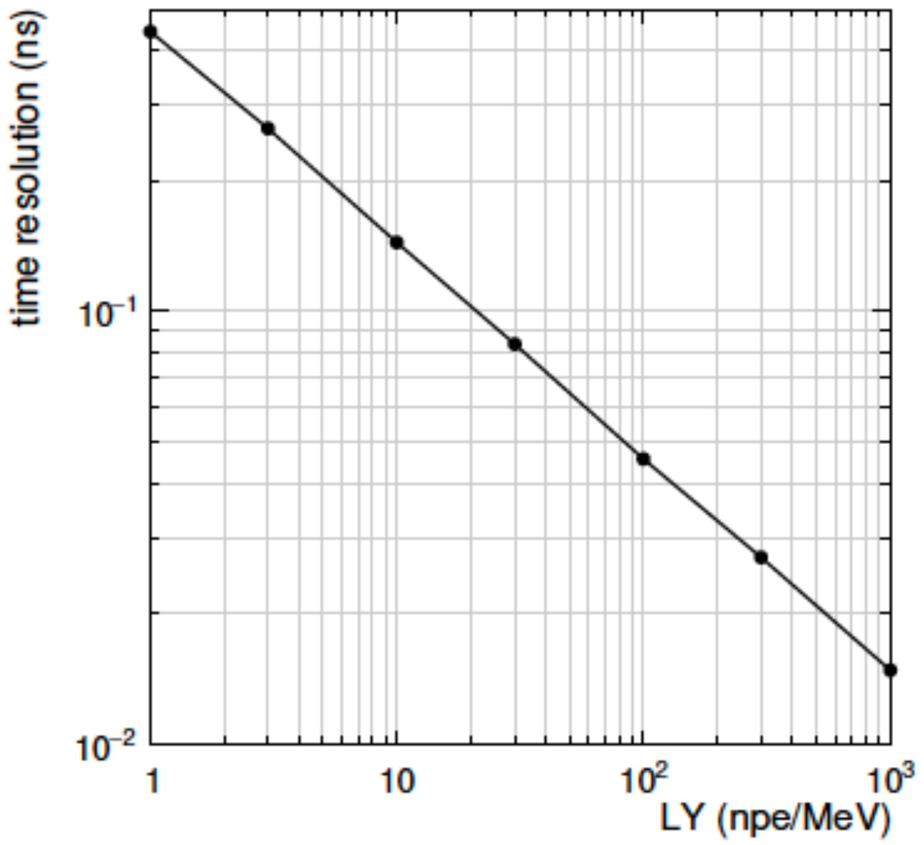


We are developing:

1. Positioning of WLS filaments at Shower Max for timing studies.
2. Incorporation of dual readout for both scintillation and Cerenkov measurement – including for timing with quartz rods and the WLS capillary structures which are predominantly quartz material.

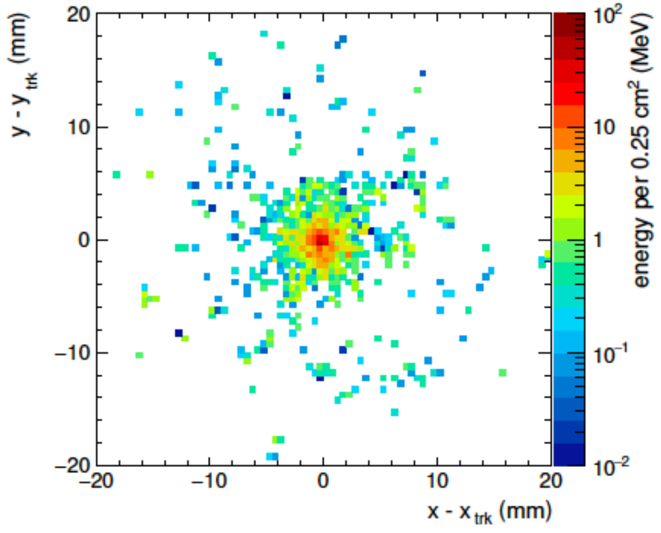


Shower Max Timing with RADICAL



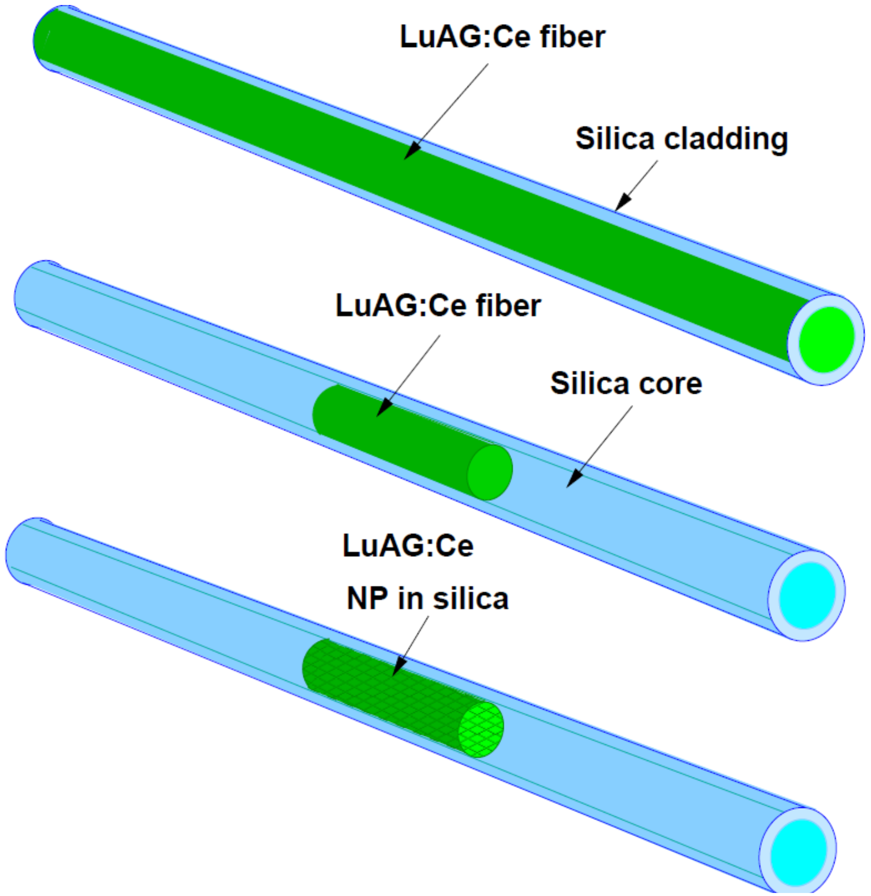
Time resolution vs detected light yield at Shower Max

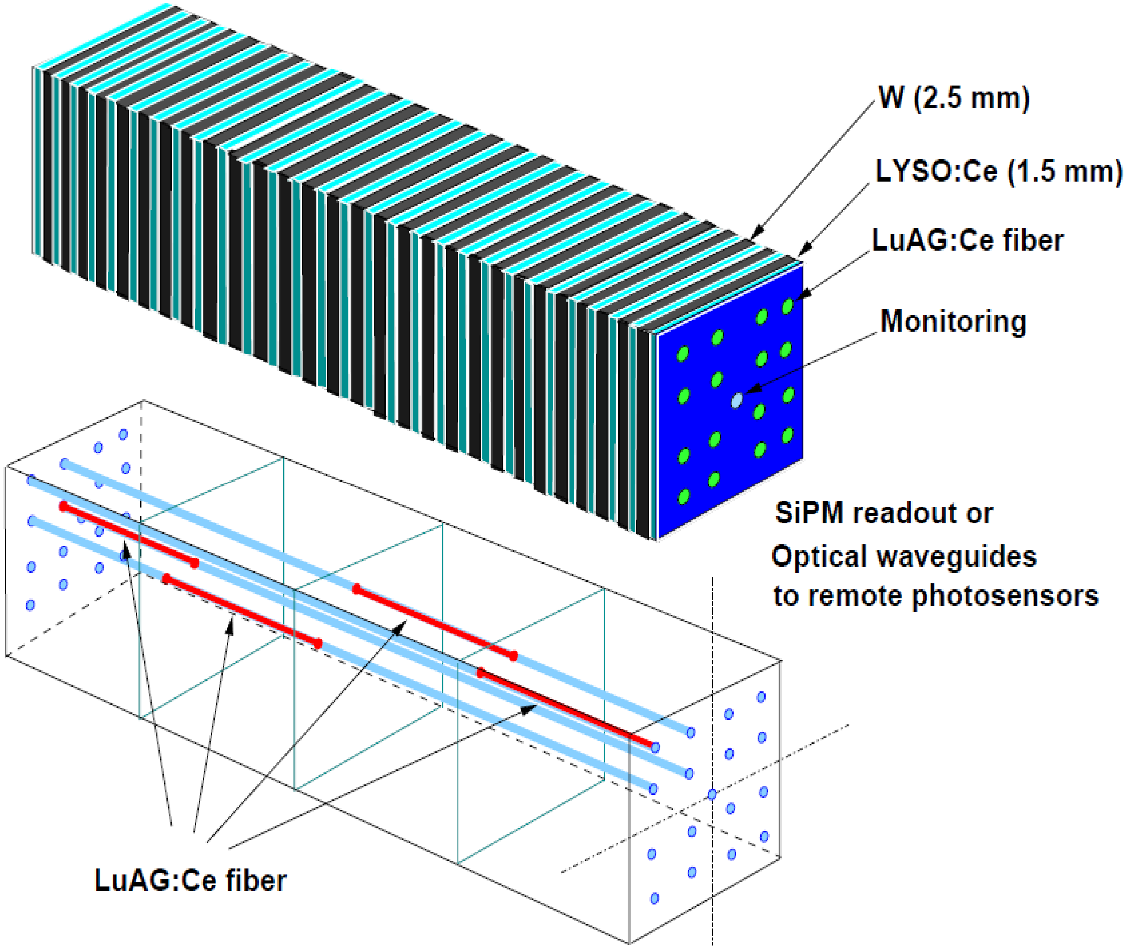
GEANT4 simulation of the time resolution expected from Shower Max, using LYSO and DSB1 filament. Electrons of 50 GeV



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

New Vision of Shower Profile Measurement with RADiCAL
Energy Sampling vs Depth to make a shower profile measurement.





Summary

- RADiCAL R&D to develop highly efficient, ultra-compact and rad hard EM calorimetry elements.

Development and testing of modular elements that can provide:

1. Energy measurement.
2. Shower Max timing measurement.
3. Shower Depth measurements for shower profile measurement.
4. Incorporation of dual readout for both scintillation and Cerenkov measurement – including for timing

- Potential applications in other areas:
  - Hadronic calorimetry
  - Forward calorimetry
  - Scintillation/WLS detection over compact and larger areas
  - Timing detectors

Work Supported by in part by:
Department of Energy: DE-SC0017810.003
National Science Foundation: NSF-PHY-1914059
University of Notre Dame: Resilience and Recovery Grant Program