RADiCAL
RADiation hard innovative CALorimetry

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

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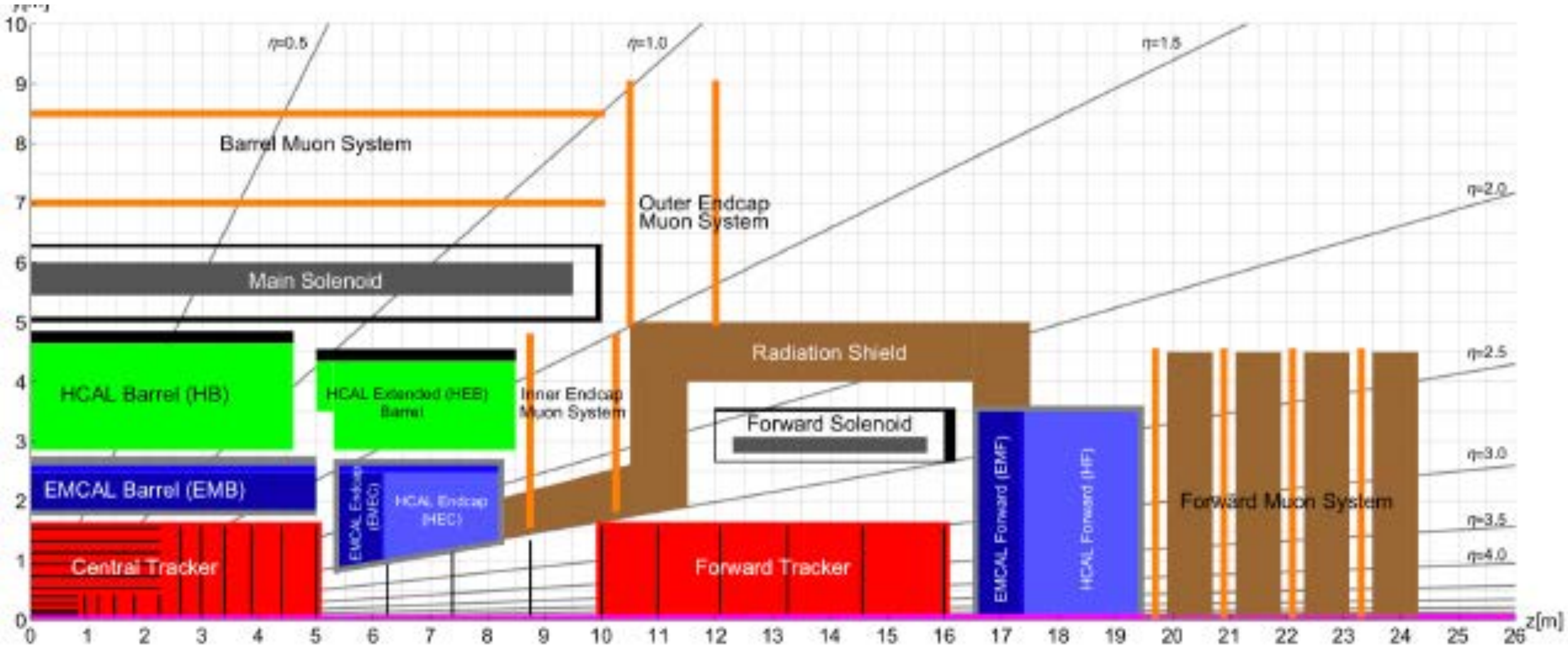
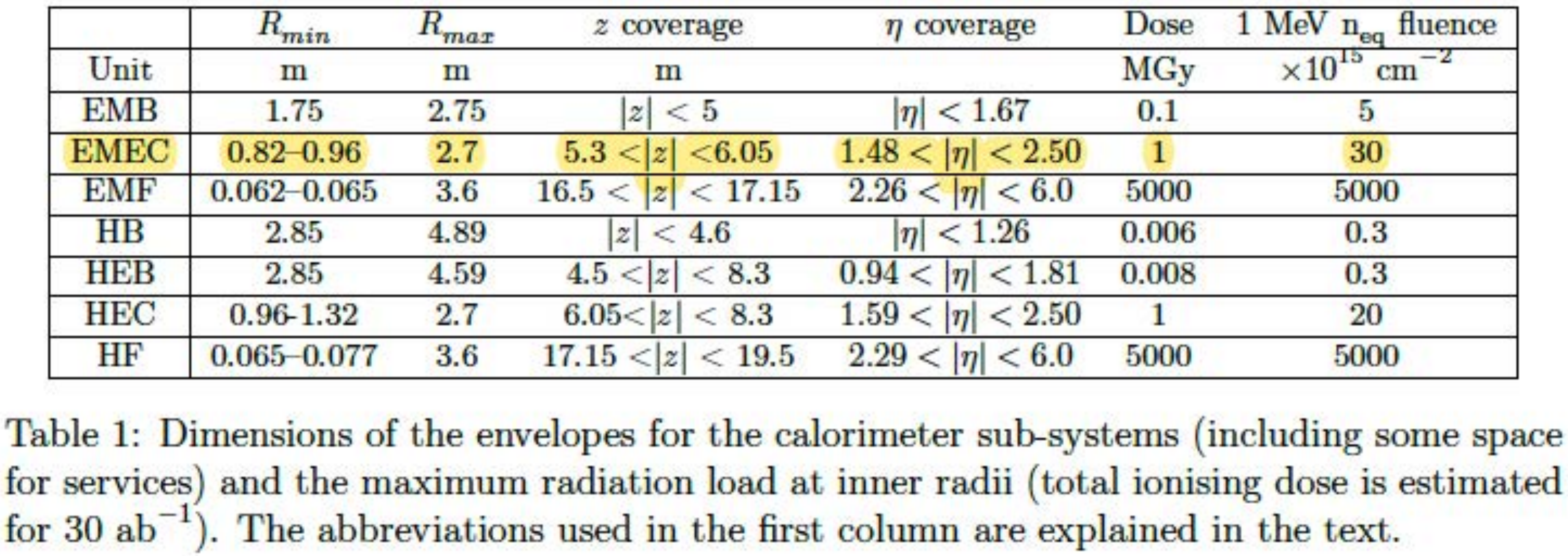




	R_{min}	R_{max}	z coverage	η coverage	Dose	1 MeV n_{eq} fluence
Unit	m	m	m		MGy	$\times 10^{15}$ cm^{-2}
EMB	1.75	2.75	$\lvert z\rvert < 5$	$\lvert\eta\rvert < 1.67$	0.1	5
EMEC	0.82–0.96	2.7	$5.3 < \lvert z\rvert < 6.05$	$1.48 < \lvert\eta\rvert < 2.50$	1	30
EMF	0.062–0.065	3.6	$16.5 < \lvert z\rvert < 17.15$	$2.26 < \lvert\eta\rvert < 6.0$	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.

RADiCAL: EM Calorimetry R&D

Desirable Features

- Excellent energy resolution
- High efficiency
- Rapid response
- Triggerability
- Good shower position
- Fast timing capability

Challenges

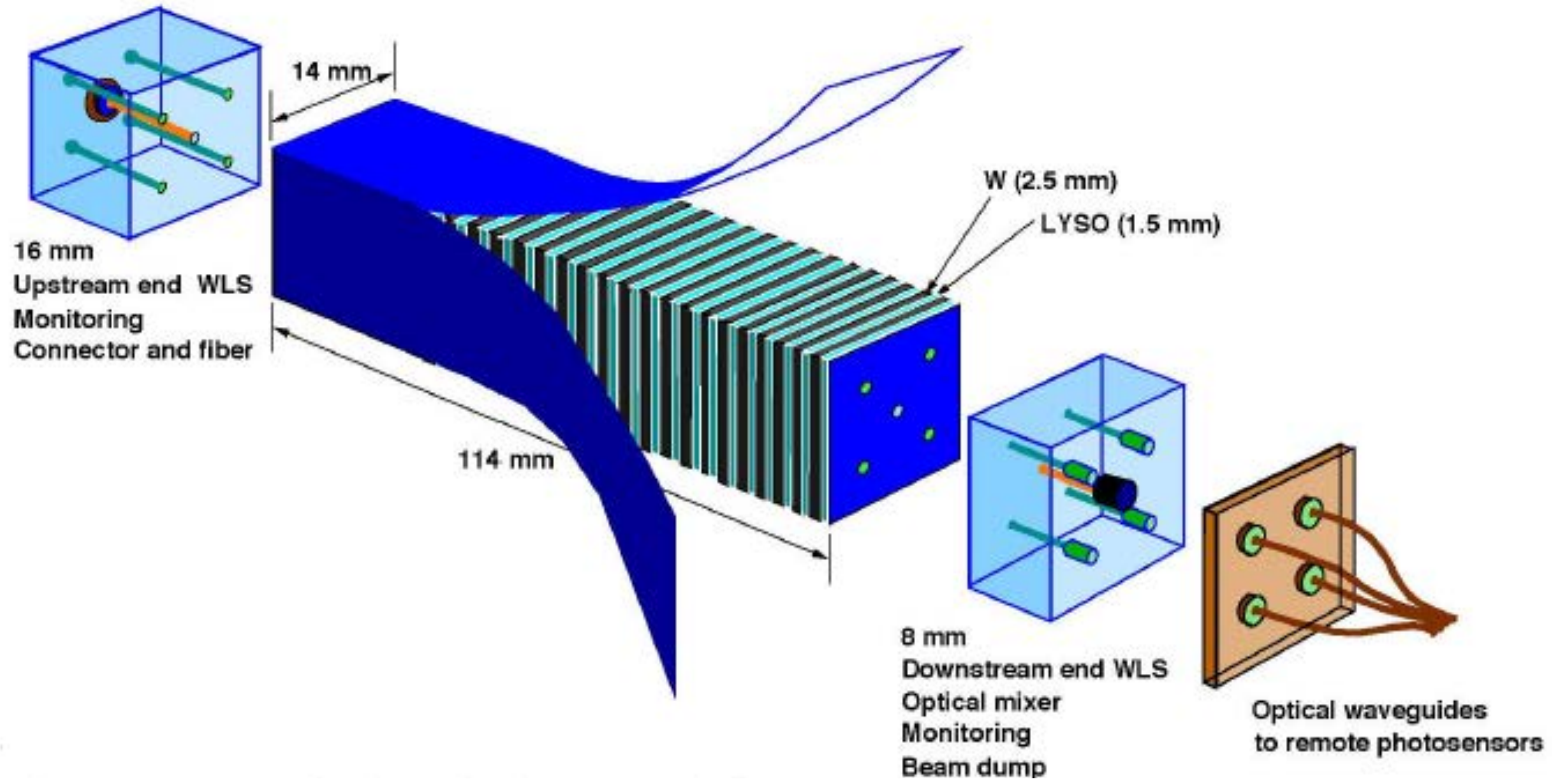
- Radiation field
  - Charged particles
  - Neutrons
- Event pileup
- Transverse Uniformity
- Longitudinal Uniformity

RADiCAL: EM Calorimetry Approach

- Objectives
  - Energy Resolution: $\sigma_E/E = 10\%/\sqrt{E} \oplus 0.3/E \oplus 0.7\%$ up to $|\eta| < 4$.
  - Fast timing response.
  - Good performance under FCC-hh operating conditions
- Technique - Sampling Calorimetry
  1. Use of dense materials to minimize transverse size and depth
     - Maintaining the Molière Radius as small as possible
     - Modular material material with depth > 25 X_o but < 1 λ
  2. Use of radiation resistant materials and elements
     - Active elements including crystal/ceramic scintillators and waveshifters
     - Optical transfer elements
     - Geiger mode pixelated photosensors
  3. Use of optical techniques for fast signal collection
     - Keeping optical paths as short as possible

RADiCAL

Ultracompact Sampling EM Calorimetry Modular Element

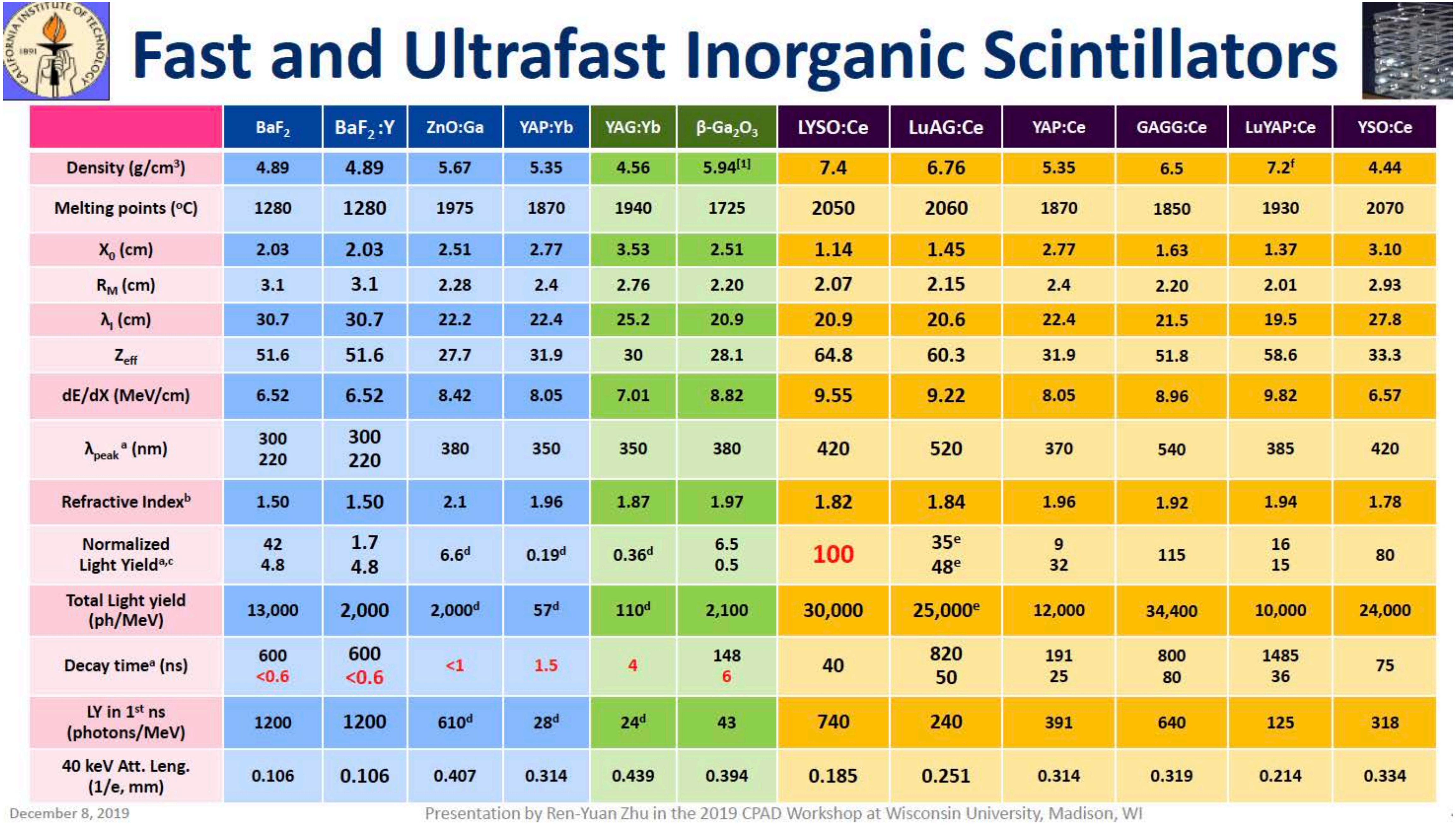


A W/LYSO:Ce Module

29 Layers LYSO:Ce (1.5mm thickness)
28 Layers W (2.5mm thickness)

Scintillation materials under investigation…

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.



Fast and Ultrafast Inorganic Scintillators

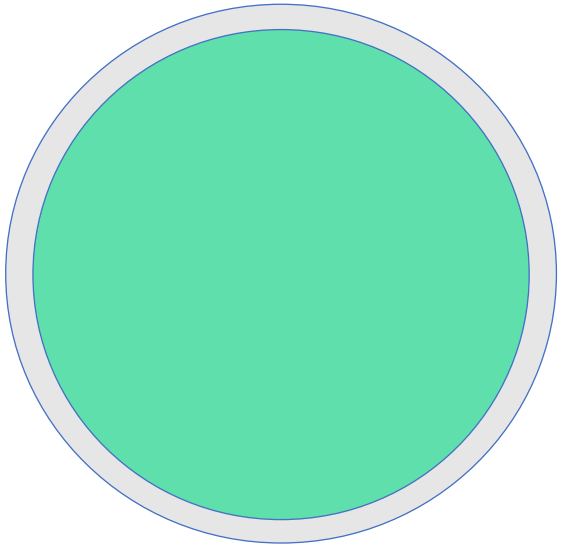
	BaF$_2$	BaF$_2$:Y	ZnO:Ga	YAP:Yb	YAG:Yb	β-Ga$_2$O$_3$	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	5.67	5.35	4.56	5.94[1]	7.4	6.76	5.35	6.5	7.2^f	4.44
Melting points (^{o}C)	1280	1280	1975	1870	1940	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	2.51	2.77	3.53	2.51	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
$\lambda_{peak}{}^a$ (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

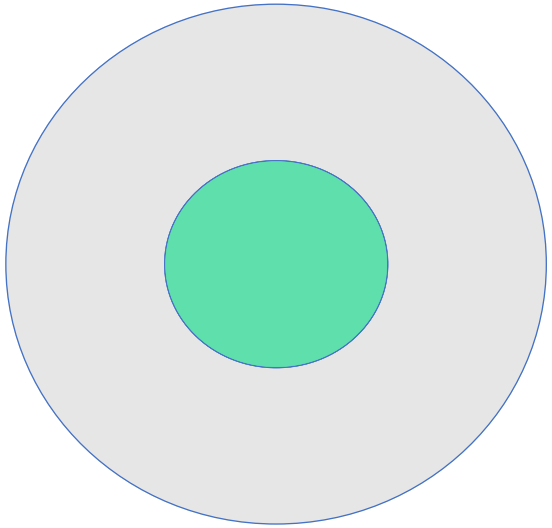
Presentation by Ren-Yuan Zhu in the 2019 CPAD Workshop at Wisconsin University, Madison, WI

Revisiting the Fiber-optic Profile

Conventional Optical Fiber



Thick Wall Profile



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

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

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 is needed.
- WLS materials specialized to different scintillators
  - To shift 420-425nm to 490-500nm, WLS dyes DSB1 and DSF1
    - Fast decay time and high efficiency
  - To shift 350-380nm to 530-560nm, WLS dyes based on hydroxyflavones
    - Rapid decay time, good efficiency and very long path length light transmission
  - Quantum Dot/siloxane and glass composites
- 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 Technology
  - 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 (530-560nm)
  - 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) for efficiency and response time.

Photosensor development

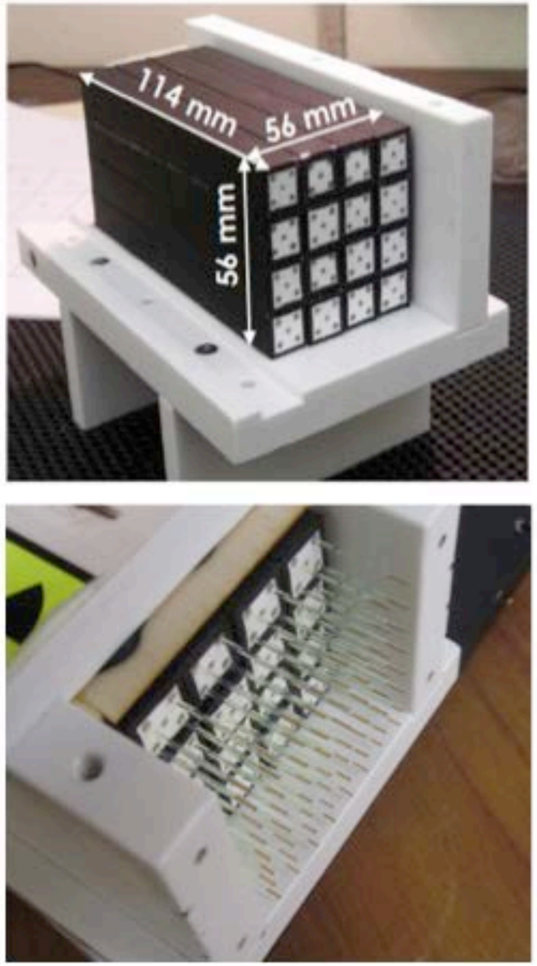
- Larger Band-gap Technologies
  - Hold promise for operation in very high radiation environments, but it is still rather early days in this R&D in spite of several device versions produced.
  - GaInP pixelated devices have been fabricated.
  - Individual photon counting seen, similar to SiPM.
  - Device optimization needed to reduce surface currents seen in the latest version.

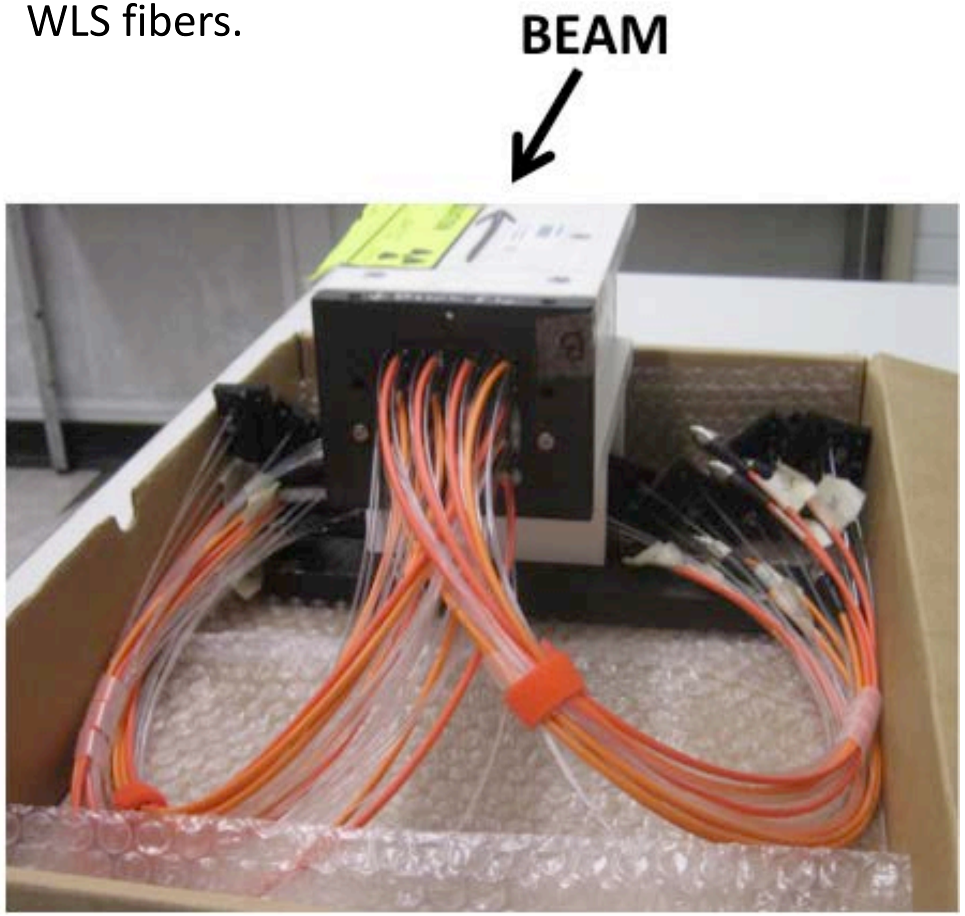
  - Challenge here is the lack (currently) of a broad commercial market to help drive development. Seeking interested industrial partnerships.

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

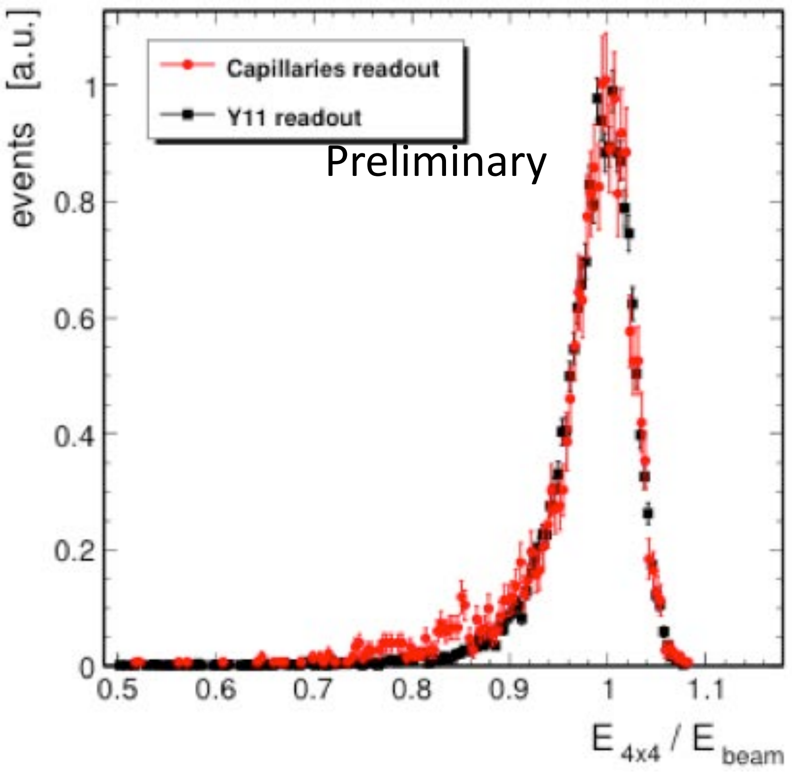
Beam Test
Caltech, Iowa
Notre Dame
Virginia

Array tested at CERN H4 and performance compared with earlier measurements using Y11 WLS fibers.

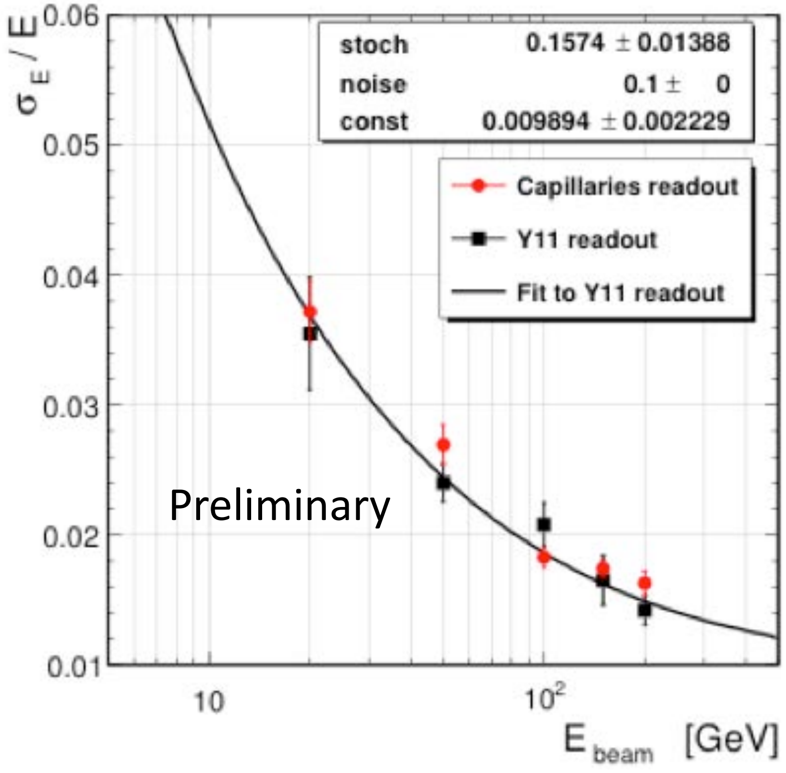




Energy Resolution of the compact 4x4 array of W/LYSO modules.

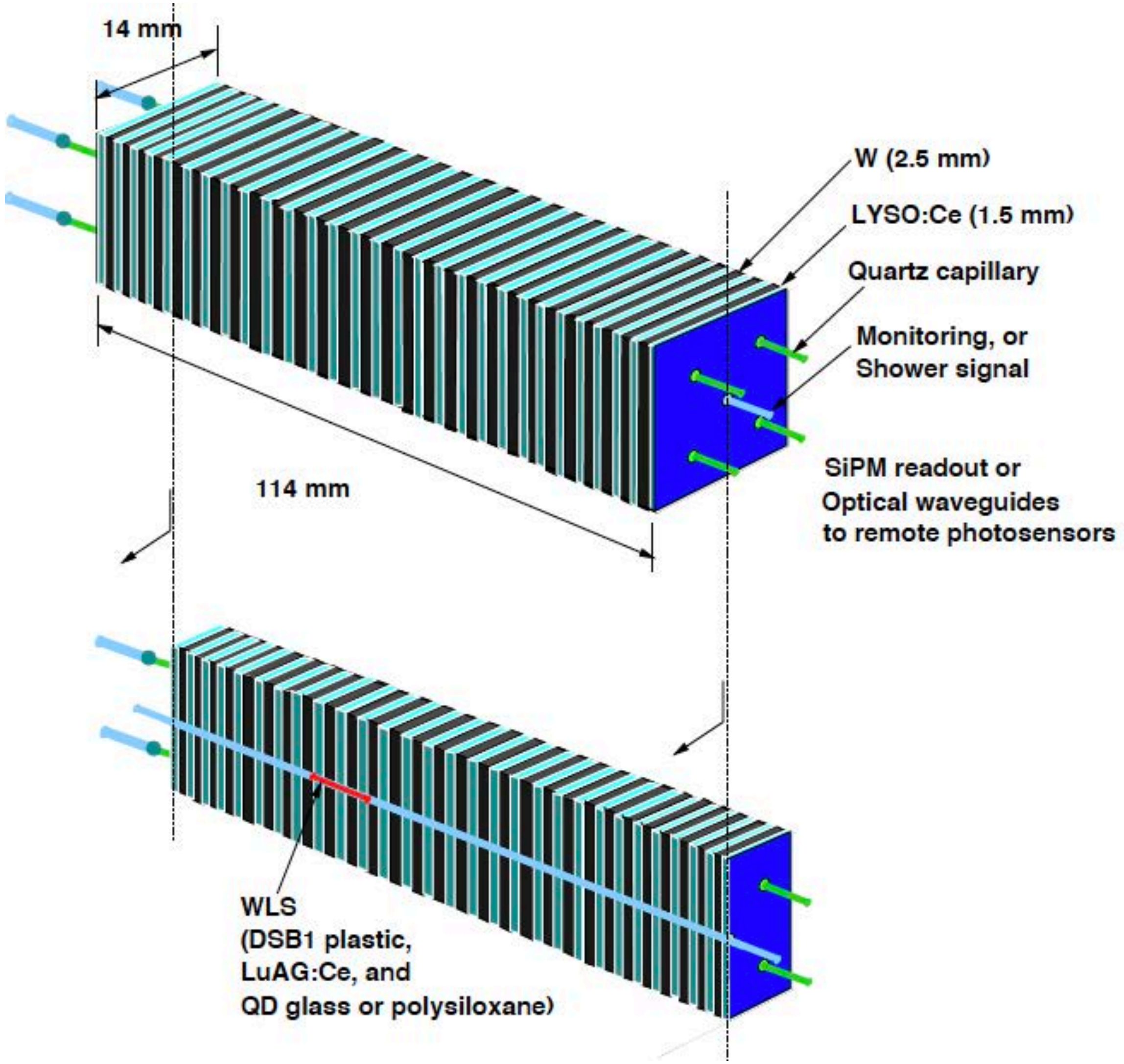


Measured 4x4 energy compared to the CERN H4 beam energy for 100 GeV electrons.



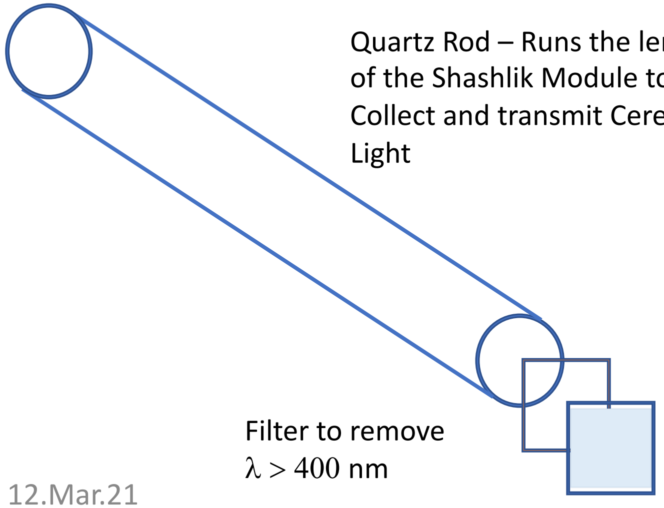
Energy resolution vs electron beam energy. CERN H4.

RADiCAL Shower Max Timing Element



We are studying the options:

1. Full energy measurement.
2. Shower Max timing measurement
3. Shower Depth measurements with sampling from various locations
4. Incorporate dual readout for both scintillation and Cerenkov measurement – including for timing

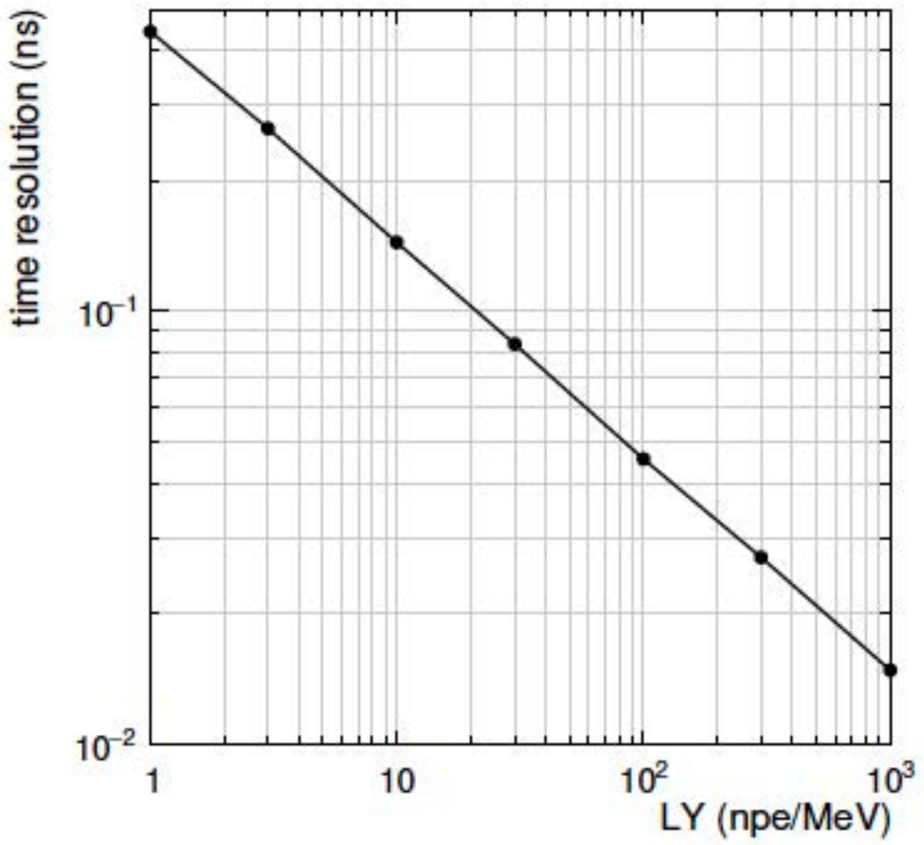


Quartz Rod – Runs the length of the Shashlik Module to Collect and transmit Cerenkov Light

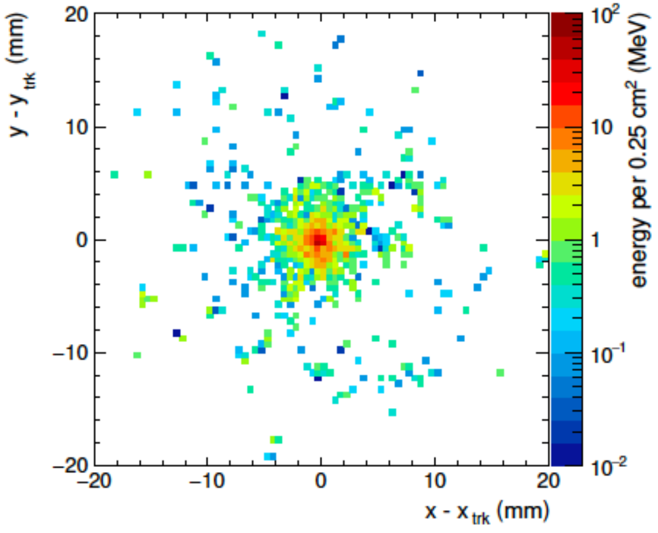
Filter to remove $\lambda > 400$ nm

UV Optimized SiPM or Other photosensor. Very High QE and fast response.

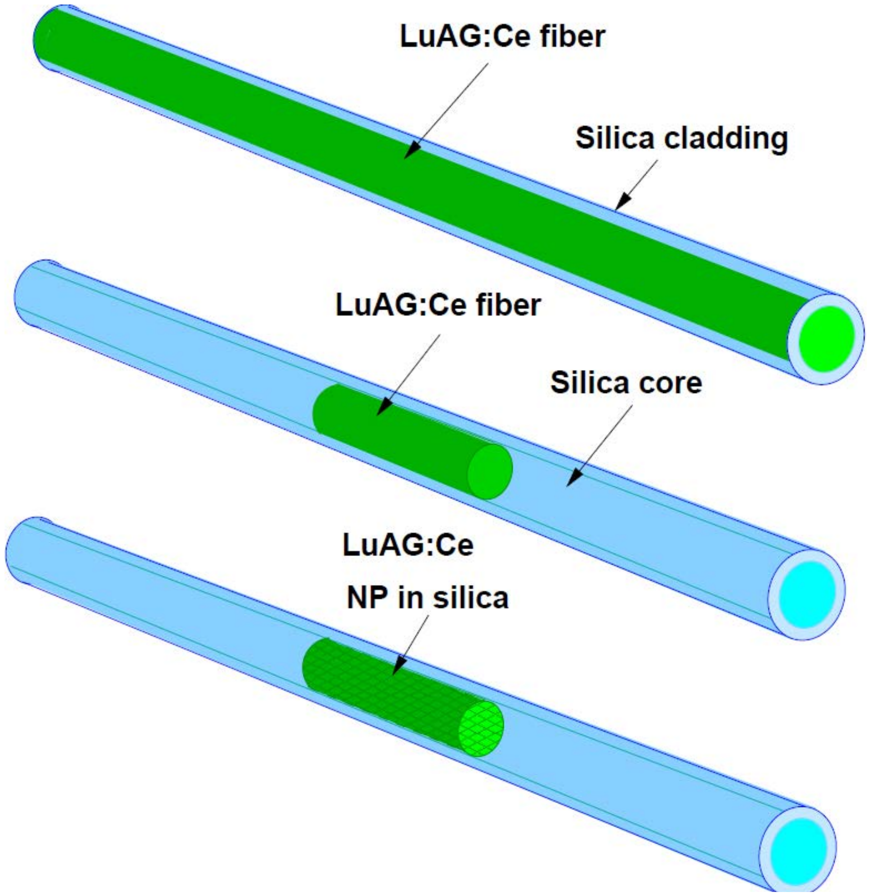
Shower Max Timing

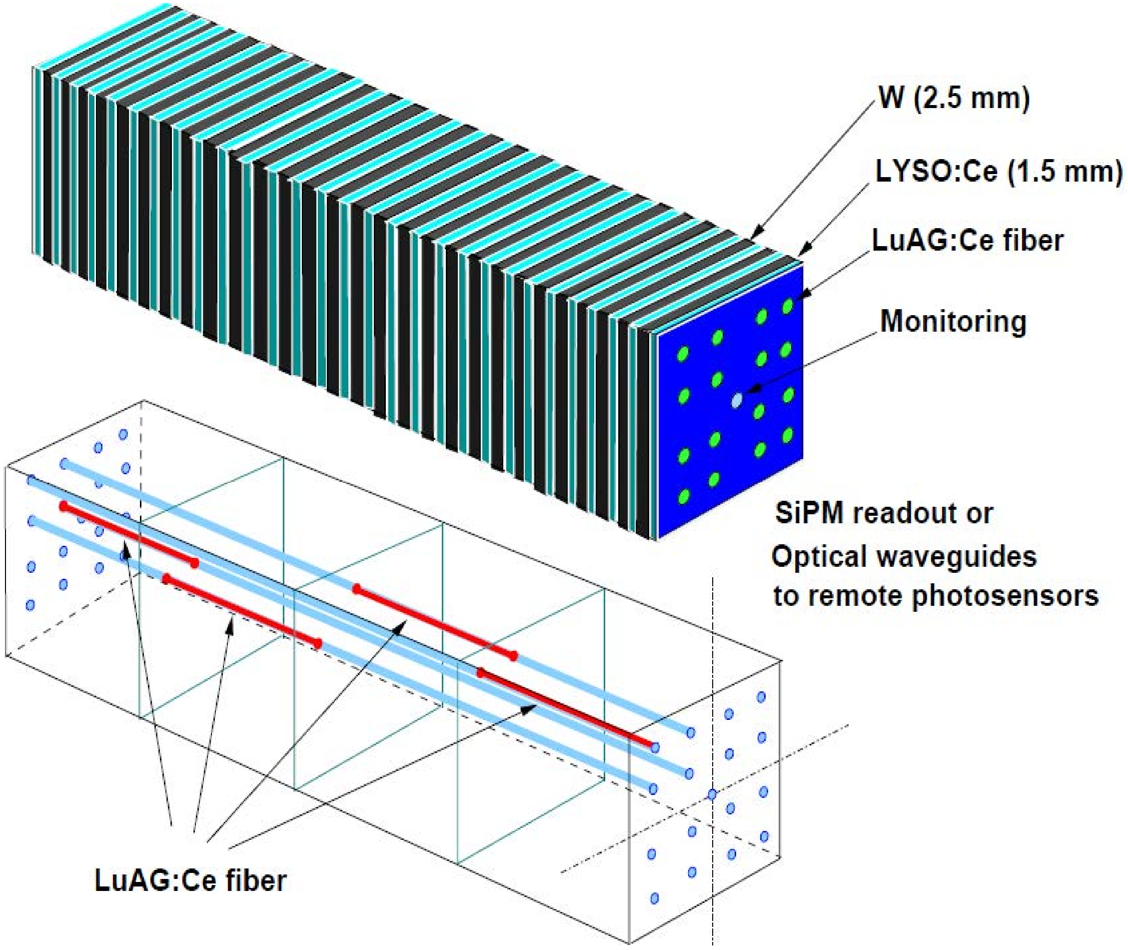


GEANT4 simulation of the time resolution expected from Shower Max, using LYSO and DSB1 filament. Electrons of 50 GeV



Energy sampling vs depth to measure shower profile





Summary

- R&D to develop highly efficient, compact and rad hard EM calorimetry elements.
- Applications are broad too.
  - Hadronic calorimetry
  - Forward calorimetry
  - Scintillation detection over compact and larger areas
  - Timing applications
- Applications to other research fields.

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