RADiCAL - Ultracompact Radiation-hard Fast-timing EM Calorimetry

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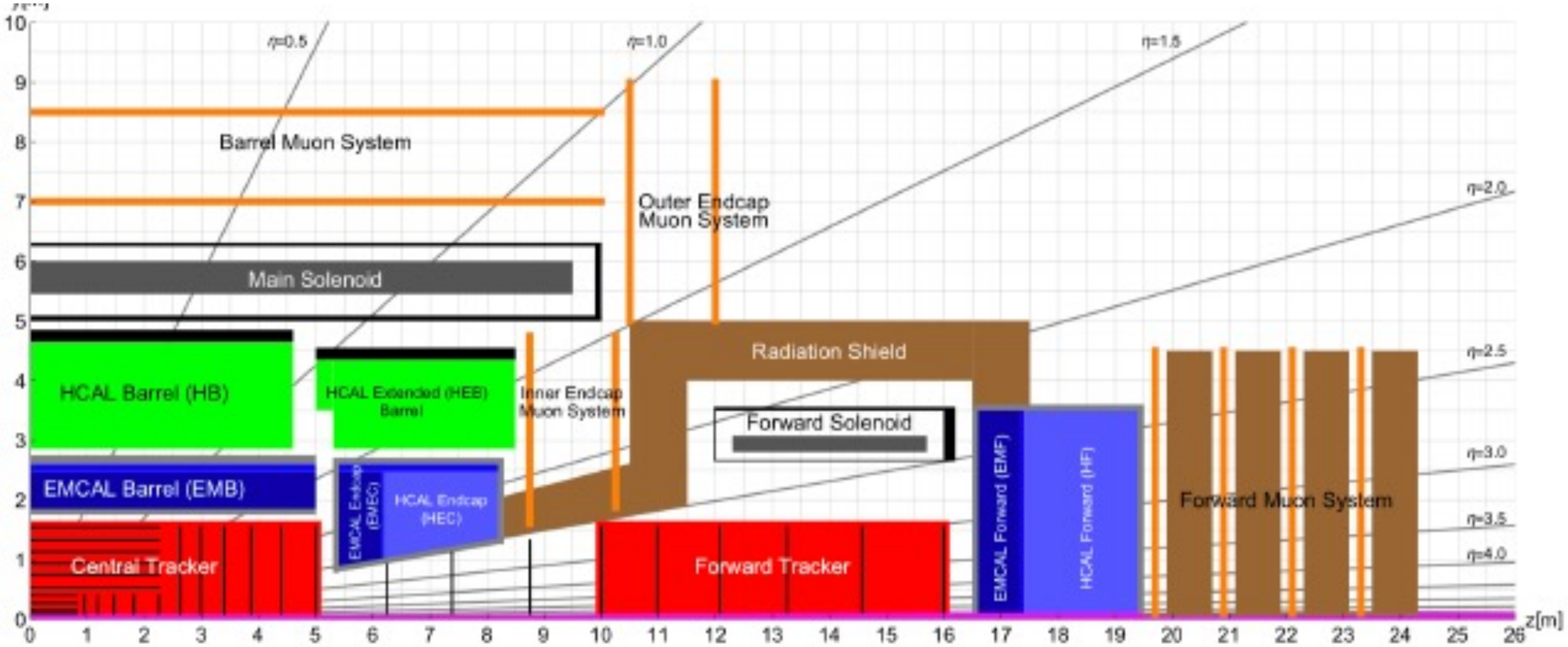
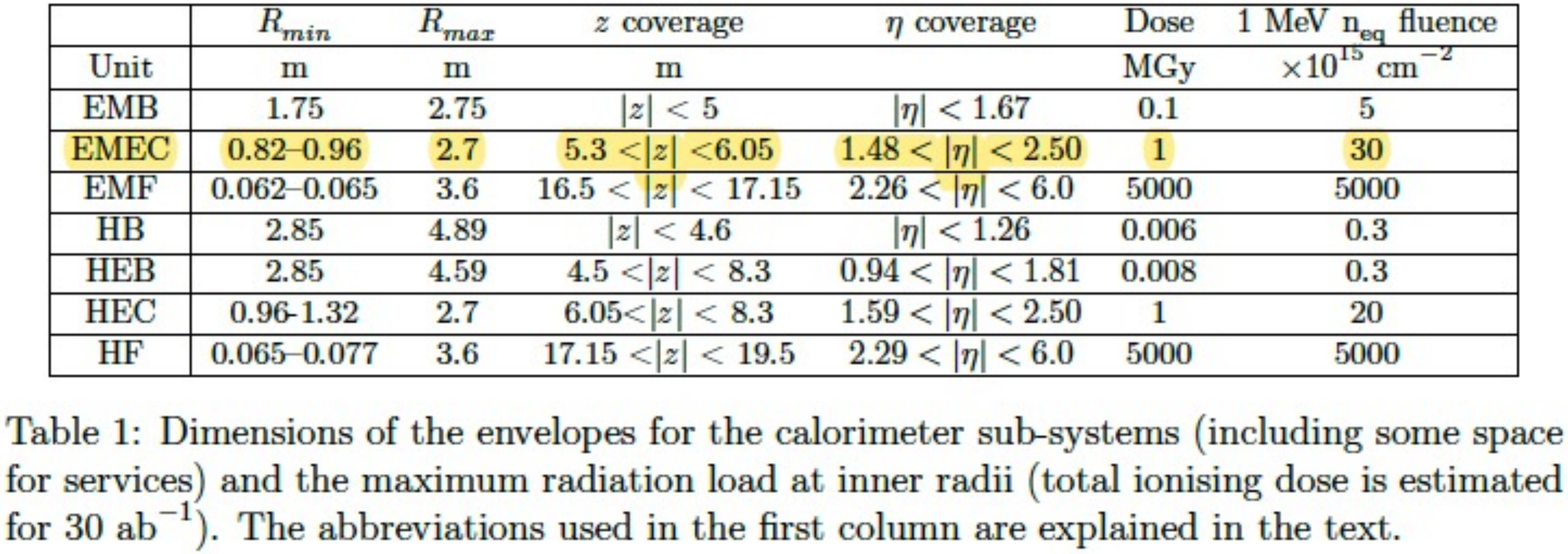




	R_{min}	R_{max}	z coverage	η coverage	Dose	1 MeV n_{eq} fluence
Unit	m	m	m		MGy	$\times 10^{15}$ cm^{-2}
EMB	1.75	2.75	$\|z\| < 5$	$\|\eta\| < 1.67$	0.1	5
EMEC	0.82–0.96	2.7	$5.3 < \|z\| < 6.05$	$1.48 < \|\eta\| < 2.50$	1	30
EMF	0.062–0.065	3.6	$16.5 < \|z\| < 17.15$	$2.26 < \|\eta\| < 6.0$	5000	5000
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 - 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 Properties

- Excellent energy resolution
- Fast response (timing capability)

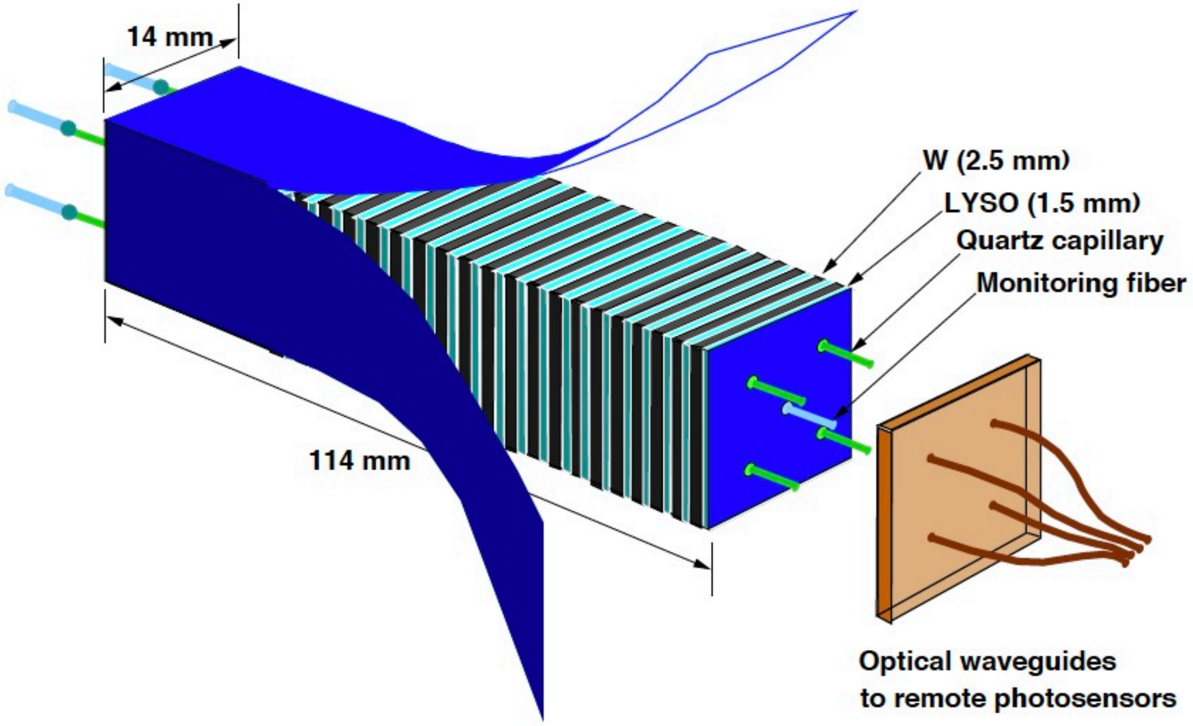
Challenges

- Radiation Environment
- Event pileup

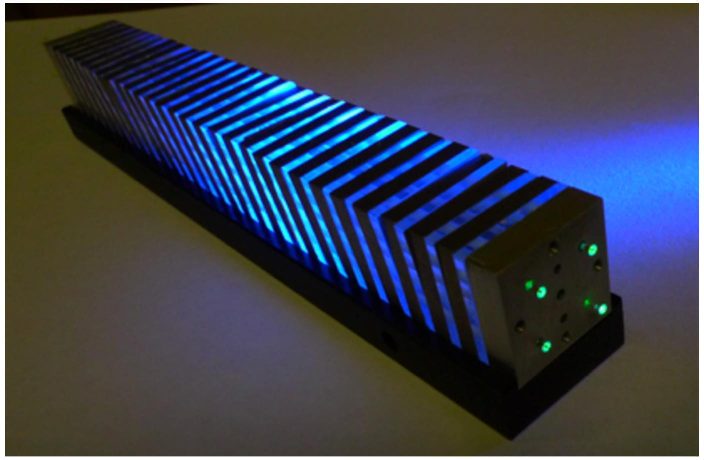
RADiCAL Approach

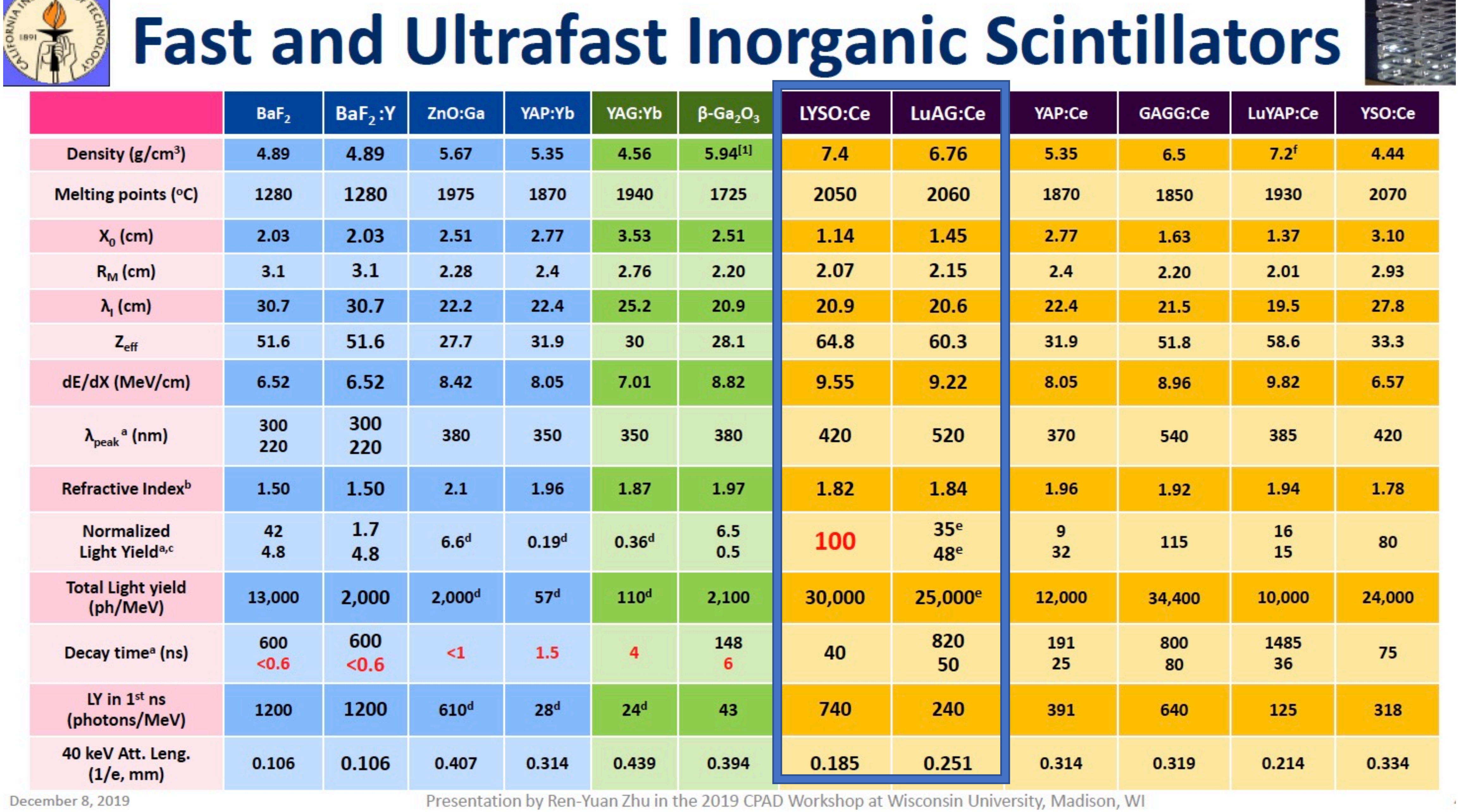
- Very Compact Dimensions
- Ultracompact, Radiation Hard Sampling Calorimetry
- Use of dense materials
  - Small Molière Radius
  - Depth > 25 X_o but < 1 λ
- Optical techniques for fast signal collection

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



- Scintillators
  - Crystals
  - Ceramics
- Wavelength Shifters
  - Fluorescent dyes
  - Liquids
  - Ceramics
- Optical Transmission Elements
  - Fiber optics
  - Capillaries
- Photosensors
  - SiPM
  - GaInP





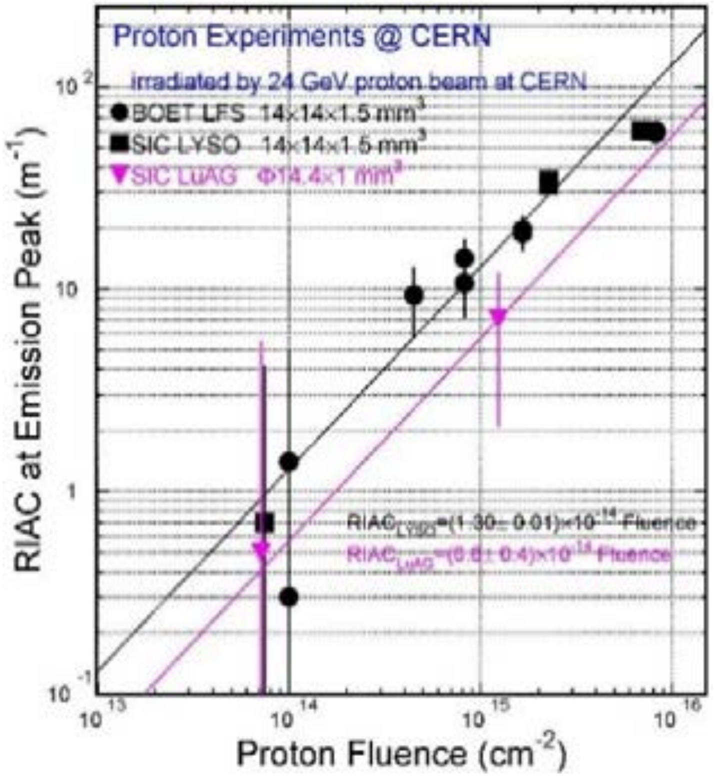
Fast and Ultrafast Inorganic Scintillators

	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

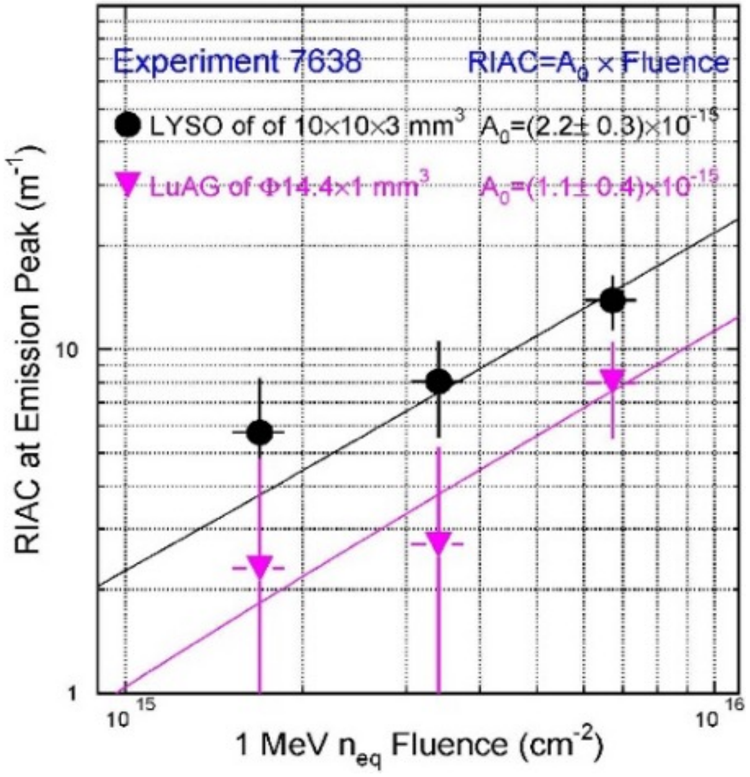
December 8, 2019

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

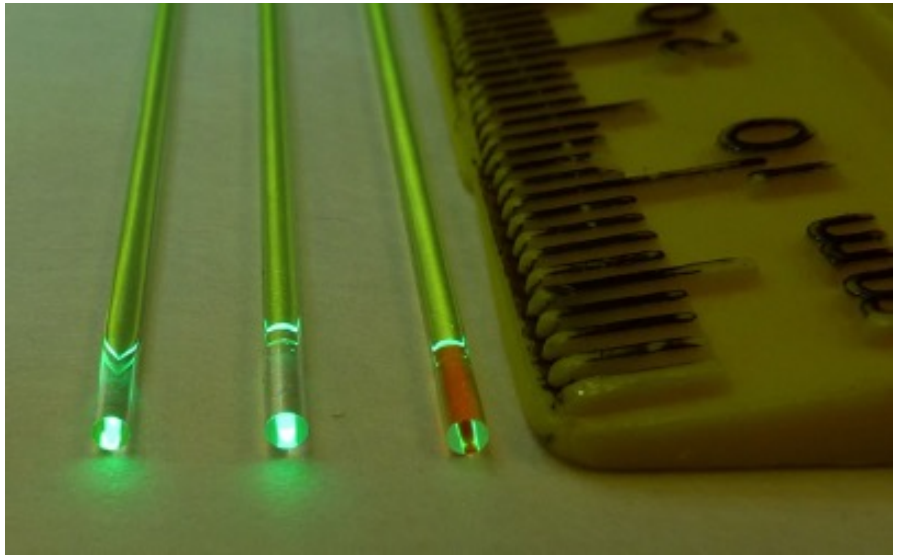


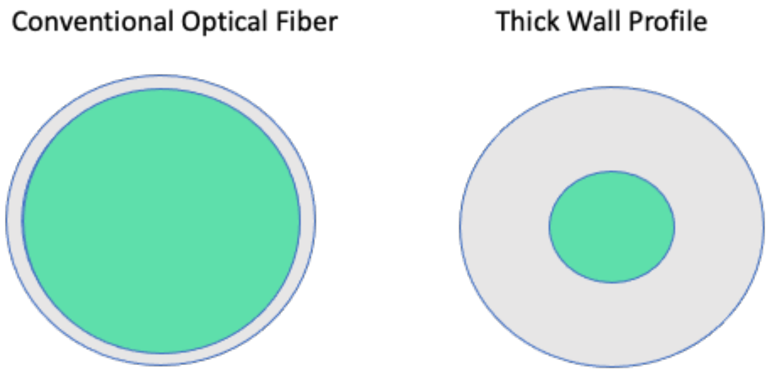
RIAC values as a function of proton fluence for LYSO/LFS crystals and LuAG ceramics irradiated at CERN



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

New visions of the Fiberoptic Profile

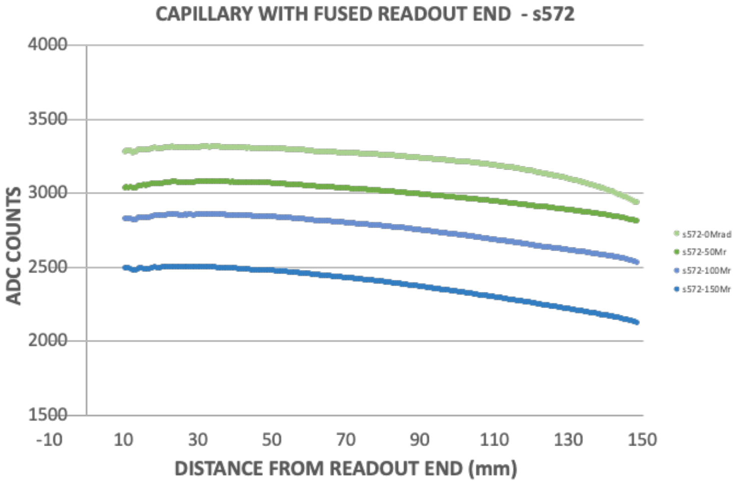


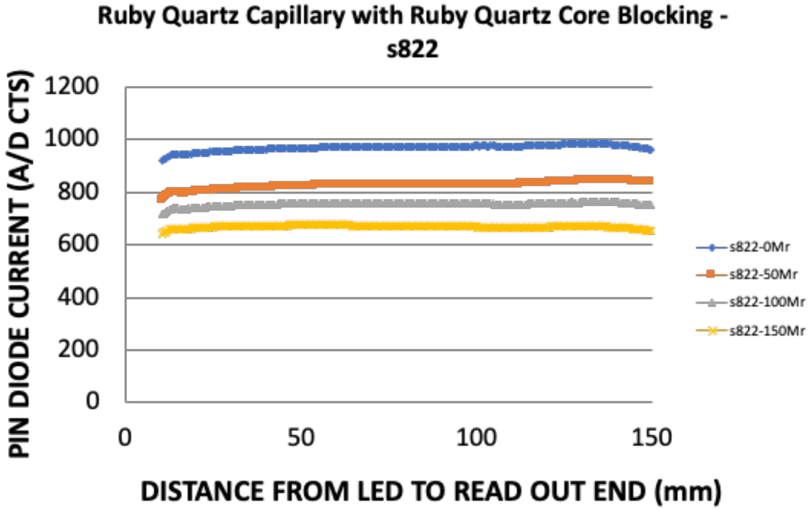


- Optical Path in WLS medium is maximal.
- Whole structure – typically polymer - is not rad hard.

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

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

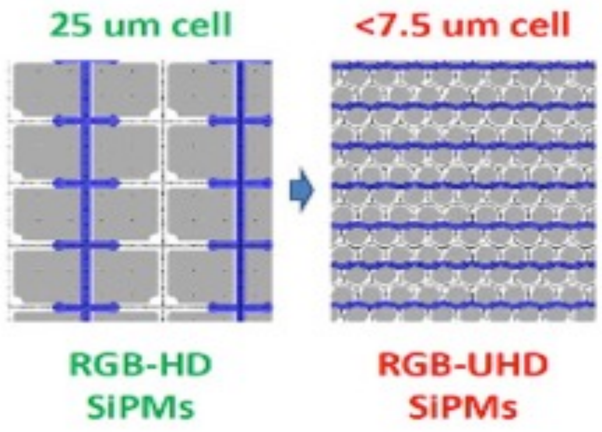




Wavelength shifters and optical transmission elements under investigation…

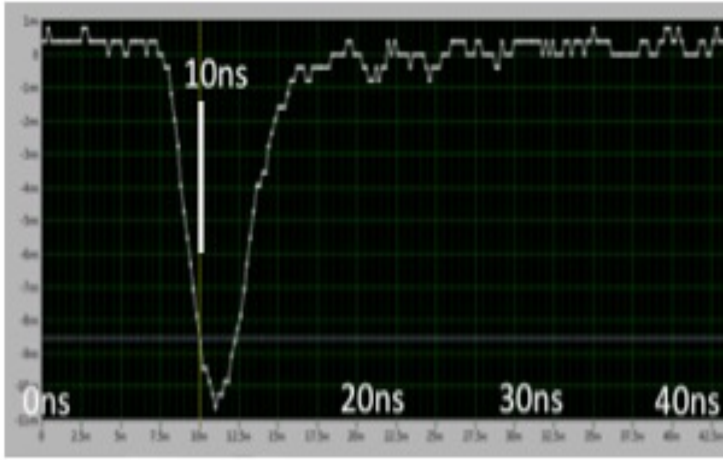
- WLS materials specialized to different scintillators
  - To shift LYSO:Ce 420-425nm -> 490-500nm, WLS dyes DSB1, J2
    -> 520 nm, LuAG:Ce
  - To shift LuAG:Pr 330-350nm -> 530-560nm, WLS dyes based on new hydroxyflavones
  - Quantum Dot/siloxane and glass composites to shift varied wavelengths
- Optical 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 or organic solid WLS materials
  - Quartz fibers

Photosensor Development - SiPM

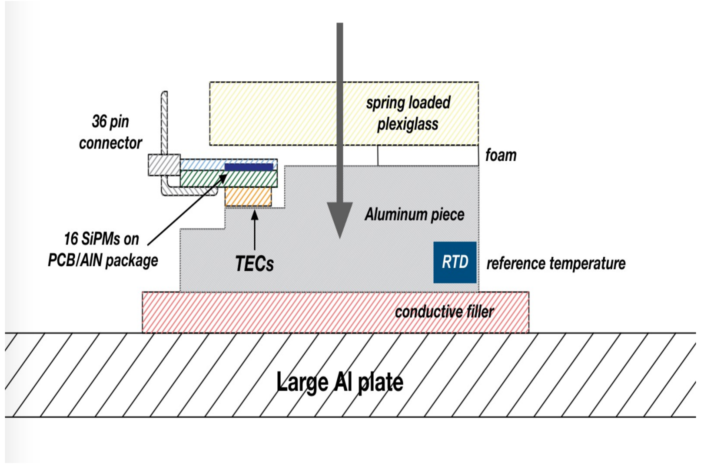


SiPM Development at FBK

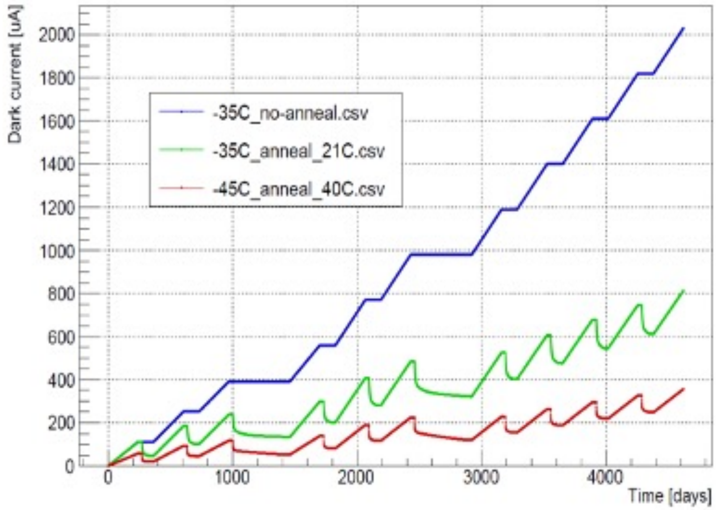
- Pixelated Geiger-mode devices with high photo efficiency across a broad spectral range.
- Particularly effective for longer wavelength light detection.
- Intention is to exploit and further the development of localized cooling (TEC) of the SiPM to reduce noise and extend performance lifetime.
- Continue 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 (CMS)



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

Blue – (-35c operation, no annealing)

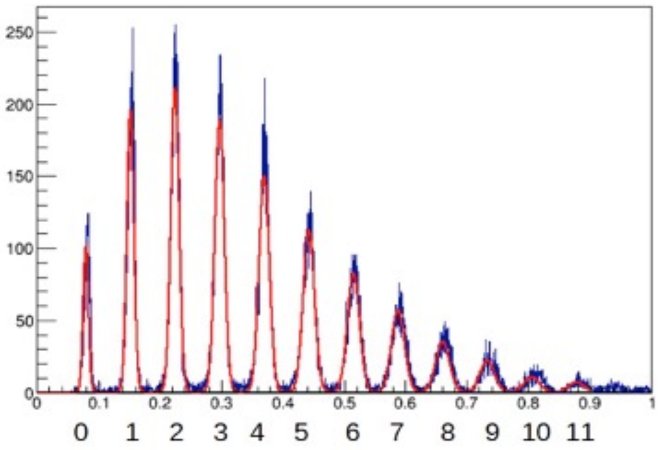
Red – (-45c operation, annealing at 40c)

Photosensor Development – Large Band Gap Devices

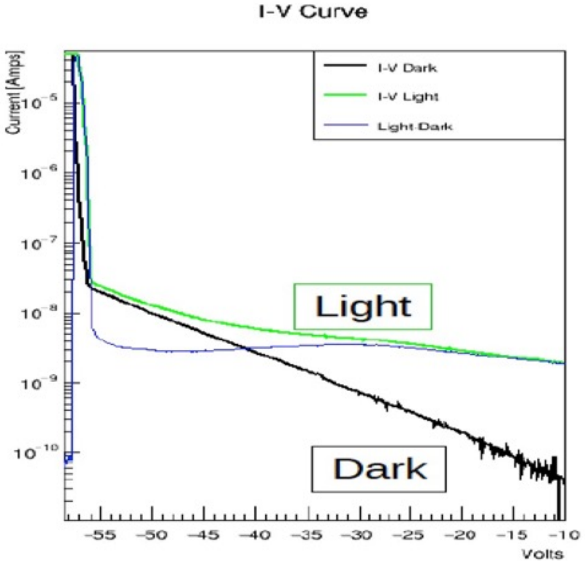
- Larger Band-gap Technologies
  - For operation in very high radiation environments
  - GaInP pixelated devices have been fabricated.
  - Individual photon counting seen, similar to SiPM.
  - Device optimization needed to reduce surface currents seen in the latest version.

  - 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

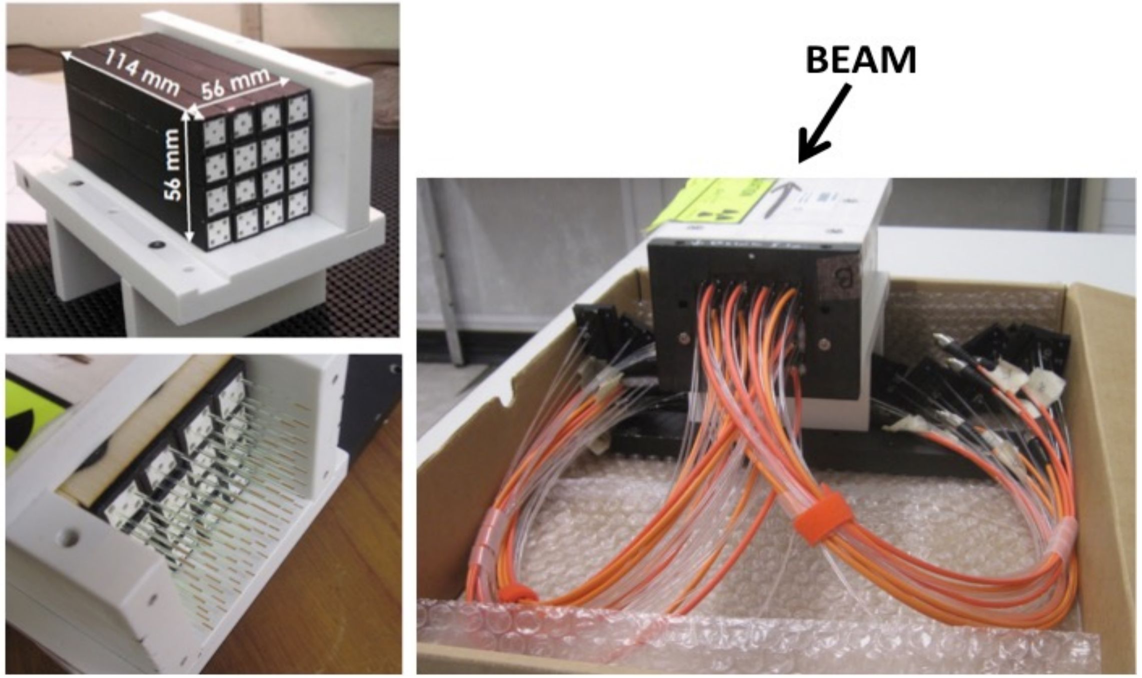


GaInP Photospectrum showing individual photopeaks. Left most (0) is the pedestal. Illumination at λ = 405nm.



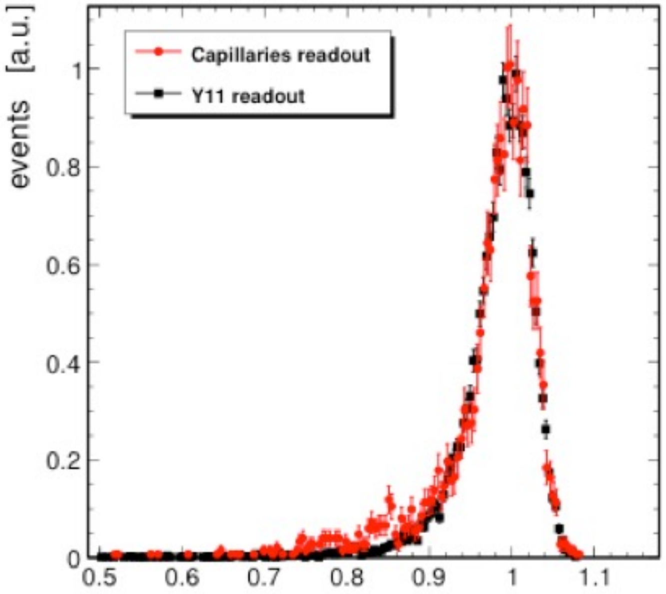
IV curves for GaInP photosensors under illumination and dark field (blue).

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

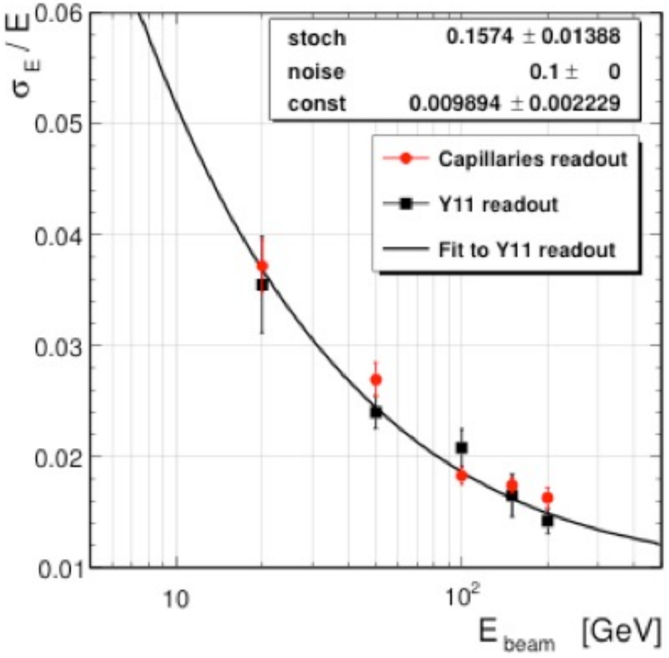


Array tested at CERN H4 with both WLS capillaries and Y11 WLS fibers.

Capillaries with the ruby core blocking

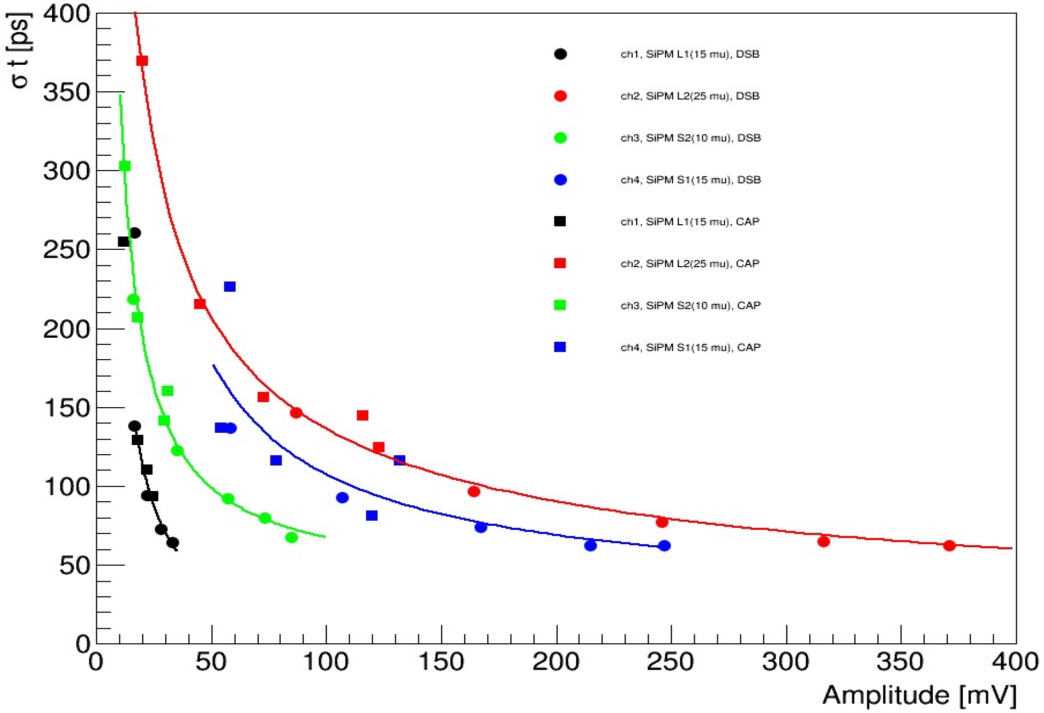


Measured 4x4 energy compared to the beam energy for 100 GeV electrons. CERN H4

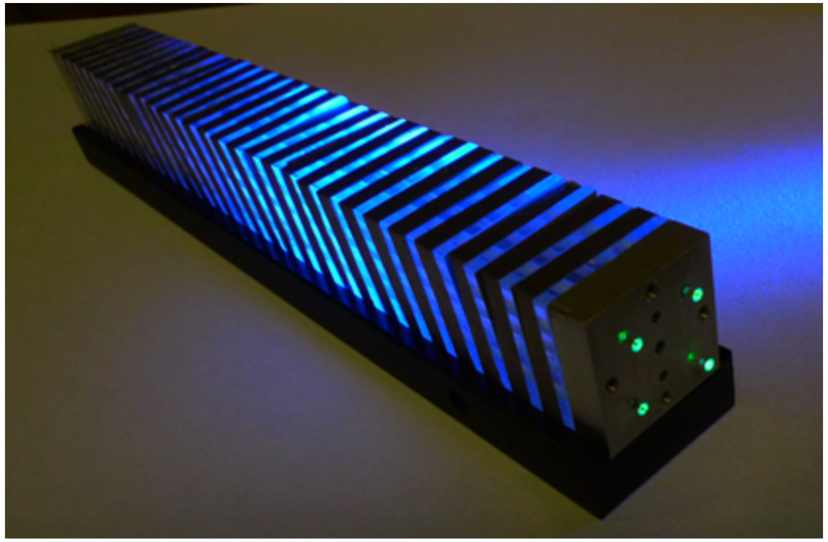


Energy resolution vs electron beam energy CERN H4.

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



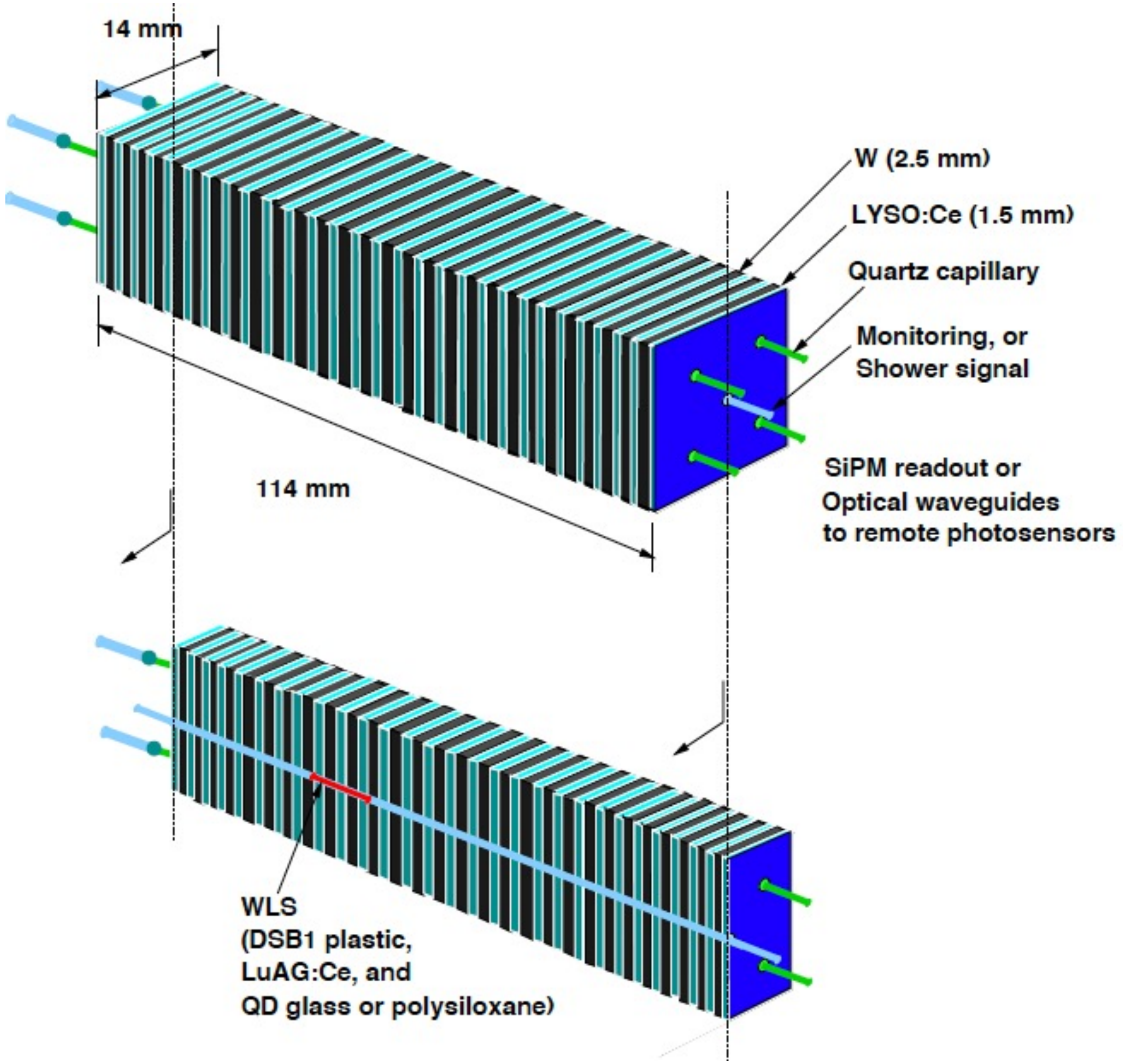
<u>LYSO/W module, single channel time resolution with SiPM readout</u>. Waveshifter readout was either DSB1 WLS dye in a multiclad optical fiber (dots) or DSB1 WLS in a liquid-filled capillary (squares). FTBF, A. Bornheim et al.



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



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.

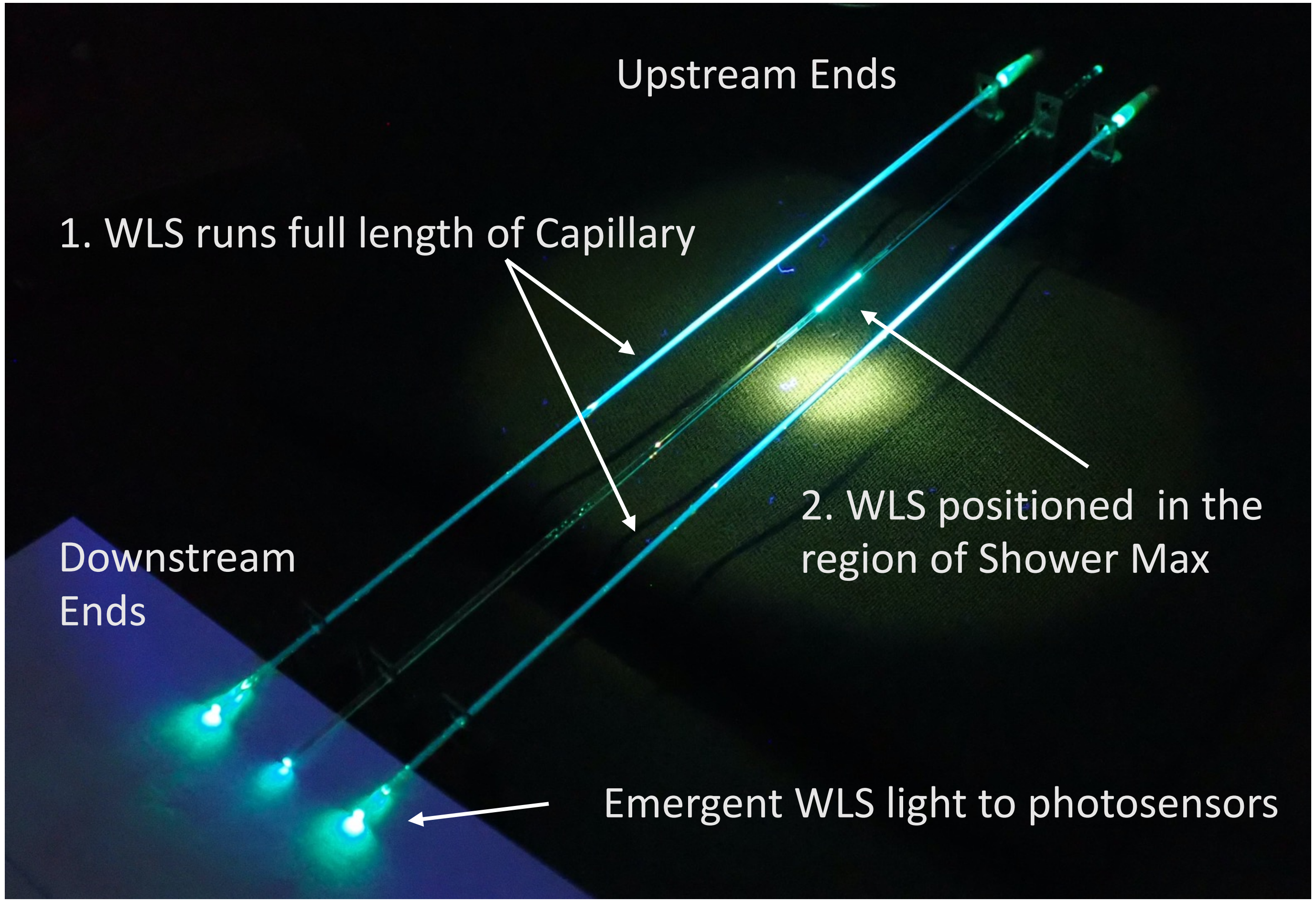
Testing:

1. Initial Beam Testing at Fermilab in late June 2021.
2. Laser pulse testing.
3. Further beam testing later in the year.

Rad-hard Quartz Capillary Structures

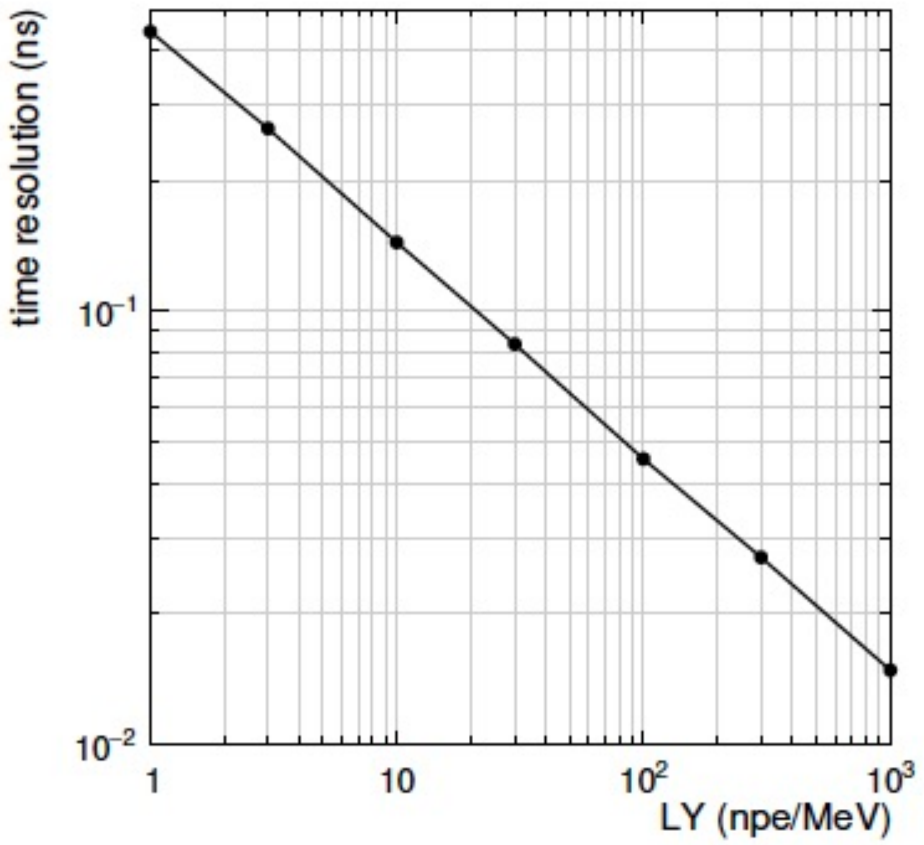
Specialized WLS Applications

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.
   - Capillary can be read out from both ends.



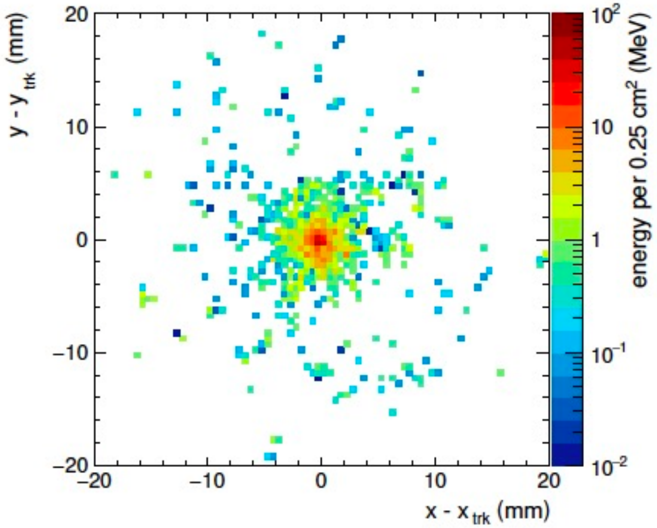
WLS Illumination by UV LED in the figure.

Shower Max Timing Simulation with RADICAL (A. Ledovskoy)



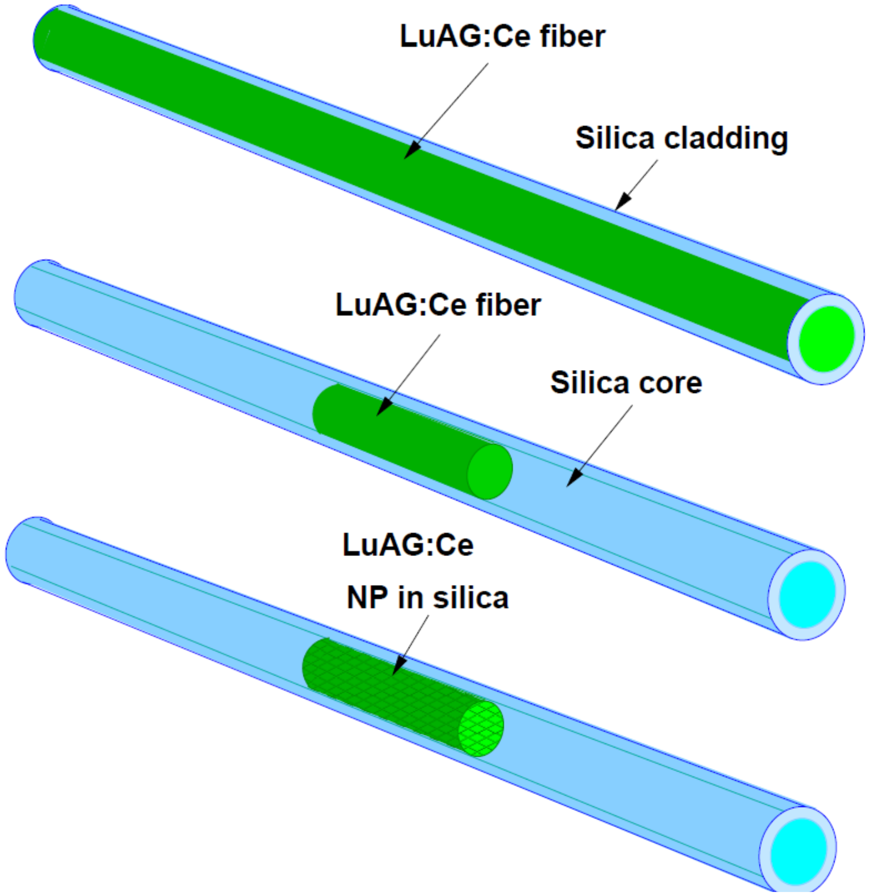
Time resolution vs detected light yield at Shower Max

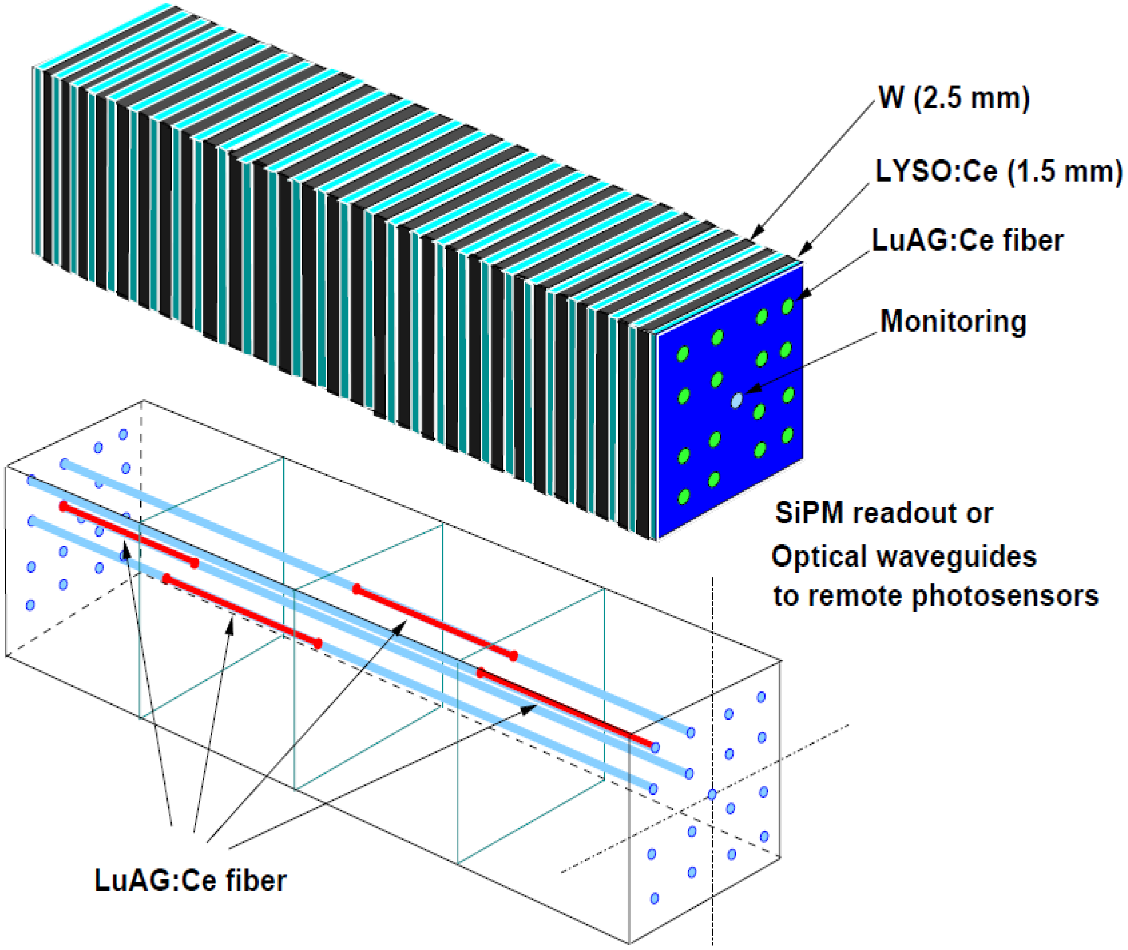
GEANT4 simulation of the time resolution expected from Shower Max, using LYSO and DSB1 filament. Electrons of 50 GeV



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 and Shower Angular measurements for shower profiling.
4. Incorporation of dual readout for both scintillation and Cerenkov measurement – including for timing

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

Work Supported by in part by:
U. S. Department of Energy: DE-SC0017810.005
U. S. National Science Foundation: NSF-PHY-1914059
University of Notre Dame: Resilience and Recovery Grant Program