Photosensors for Optical Calorimetry

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Strategies for optical calorimetry sensors have evolved over time

- In preparation for past hadron collider application:
  - Emphases were on:
    - Triggering, energy, hermeticity
    - Precision measurement of energy for EM
    - Lower precision measurement of energy for hadrons (historical view, in part driven by cost).
  - Tools included PMT, VPT, HPD, PIN Diodes, initial effective use of SiPM.
    - Wavelength ranges of light emitters were more constrained: use of bi-alkali and multi-alkali photocathodes: near UV to blue-green region typically.
- More recent approaches in anticipation of new machines (ee, hh, $\mu\mu$):
  - Emphases are on:
    - Precision measurement of energy for EM <u>and</u> for hadrons
    - Direct connection with tracking instrumentation, especially for particle-flow
    - Timing, triggering identification of EM and hadronic components for dual readout
  - Tools include: SiPM, SiPM arrays, MCD-PMT, MCP-PMT
    - Wavelength range covered is now vastly more broad: VUV to red…
    - The range of fluorescent material is correspondingly vast: crystals, ceramics, glasses, new materials…

From the DRD6 Proposal Submission Projects within WP3 and Photosensor Associations

Subtask	Project	Optical Source	Photosensor Choice	Application
3.1.1	HGCCAL	BGO, LYSO	SiPM	e+e-
3.1.2	MAXICC	PWO, BGO, BSO	SiPM	e+e-
3.1.3	Crilin	PbF_3 PWO-UF	SiPM	μ+μ-
3.2.1	GRAiNITA	$ZnWO_4$ BGO	SiPM	e+e-
3.2.2	SpaCal	GAGG, organic	MCD-PMT, SiPM	e+e-/hh
3.2.3	RADiCAL	LYSO, LuAG, DSB1	SiPM	e+e-/hh
3.3.1	DRCal	PMMA, Plastic	SiPM, MCP-PMT	e+e-
3.3.2	TileCAL	PEN, PET	SiPM	e+e-/μ+μ-/hh
3.4.1	ScintCAL	Various	Various	Optical material development
3.4.2	CryoDBDCal			Low Temperature application

Photosensor characteristics that need to be considered (not a rank ordering):

Application	EM or hadrons or both: Energy, Timing, Position
Light Source(s)	Scintillation, Wavelength shiftedlight, Cherenkov
Sensing wavelength range(s)	VUV, UV, Visible, Red, other
PDE	Photodetection Efficiency as a function of wavelength
Detector Sensor Elements - Size and Structure	Individual devices or in arrays. Pixel size.
Operating Temperature Range	Room temperature, Cold, Cryogenic, heating for annealing
Magnetic Field	Uniform Field, Fringe Field, Not applicable
Radiation Tolerance	Integrated dose of 1 MeV n_{eq}/cm^2 over lifetime Ionization dose
Detector situation	Replaceable or not
Cost implications	Scale of instrumentation coverage

Photosensor types under current use/investigation

Detector	Photosensor Locations in Detectors	Light Detection	Measurement Objectives	Photosensor options - examples
EM Calorimetry	• Crystal faces	• Scintillation • Cherenkov	Energy Timing Position	SiPM arrays: HPK S14160/S14161 SiPM: HPK HDR2 SiPM: FBK NUV-HD SiPM: FBK RGB
	• Ends of scintillating waveshifting fibers and • capillaries	• Scintillation • Waveshifter • Cherenkov	Energy Timing Position Sampling at strategic depths	PMT: R12421 MCD-MT: R7600U-20 SiPM: HPK HDR2
Hadron Calorimetry	• On scintillator tiles	• Scintillation	Energy Timing Position	SiPM: HPK HDR2
	• At ends of fibers	• Scintillation • Cherenkov	Energy Timing Position	SiPM arrays of selected pixel dimensions MCP-PMT: PLANACON XP85112, PLANACON XP85012

Photosensor choices - application driven

Detector	Photosensor Locations in Detectors	Light Detection	Measurement Objectives	Photosensor options - examples
Forward Calorimetry	Operable in high radiation Locations	Cherenkov	Hermeticity Triggering	PMT, Multi-Anode PMT, MCD-PMT
EM Calorimetry	Specialized R&D for Crystal Readout and WLS Readout	Far UV Near UV	Energy Timing	Solar Blind Sensor R&D (Mu2e-II) SiC devices? - fabricated in the past by by GE Diamond devices?
Cryogenic Calorimetry	Operable in LAr and LXe	VUV	Timing Triggering…	VUV SiPM

Some features of SiPM

Benefits

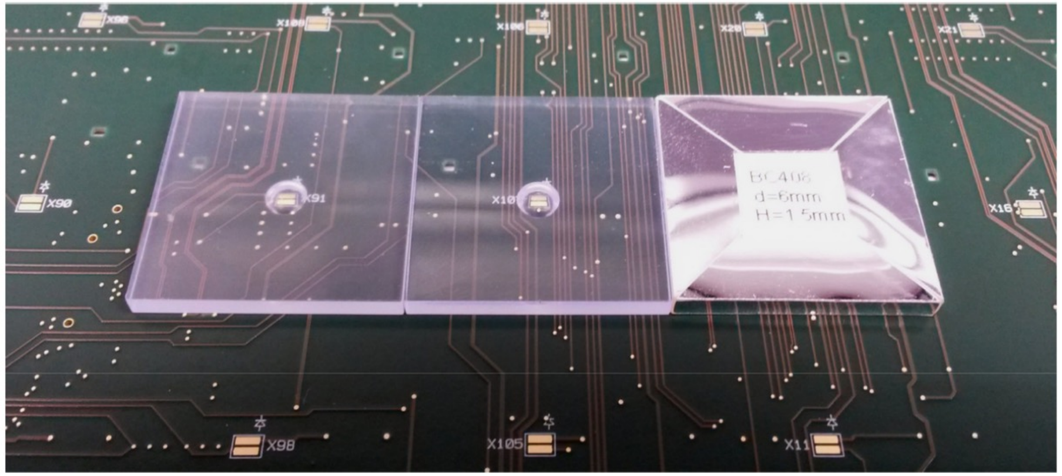
- Compact size - arrays available
- Fast response for both timing and energy
- PDE can be tuned for coverage over a wide wavelength range
- Relatively low cost per channel

Challenges

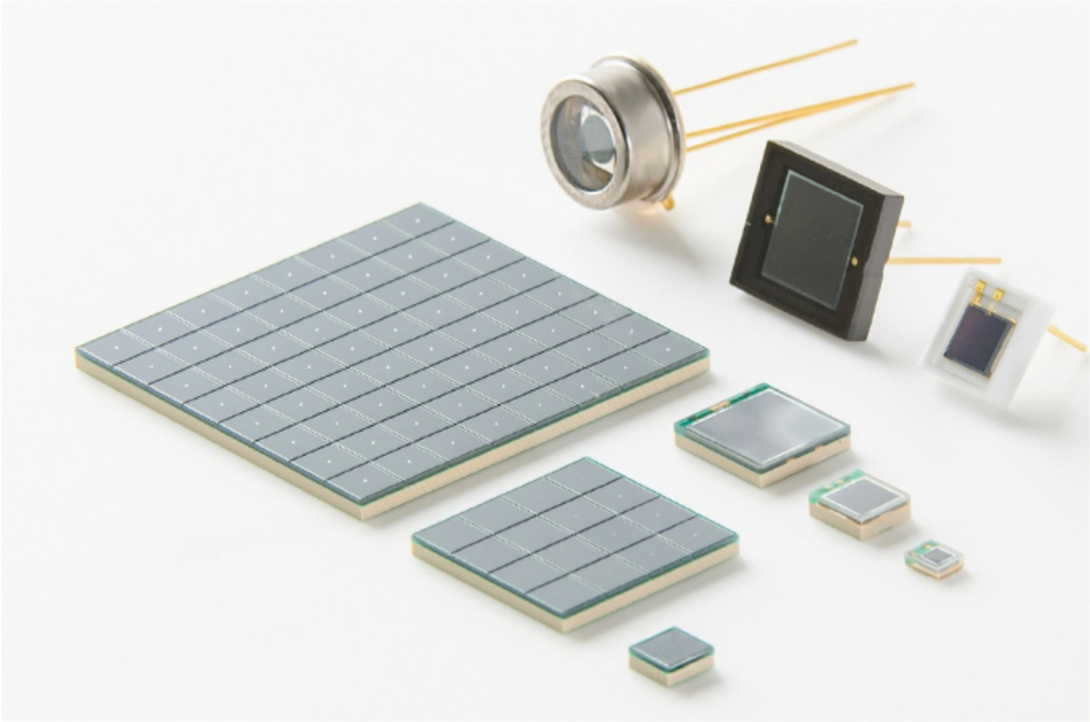
- Radiation Field
- Temperature dependence
- DCR/noise

Single SiPM- Useful for Planar Tile Structure

CMS HGCAL - Plastic Scintillator Tiles and HDR2 SiPM in dimples

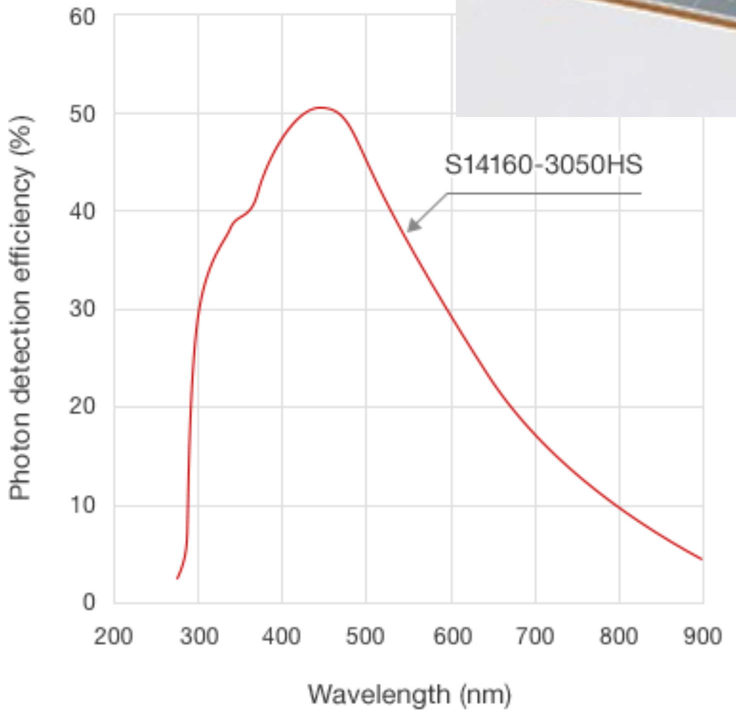


CMS HGCAL - SiPM choice was 3x3mm HDR2 SiPM

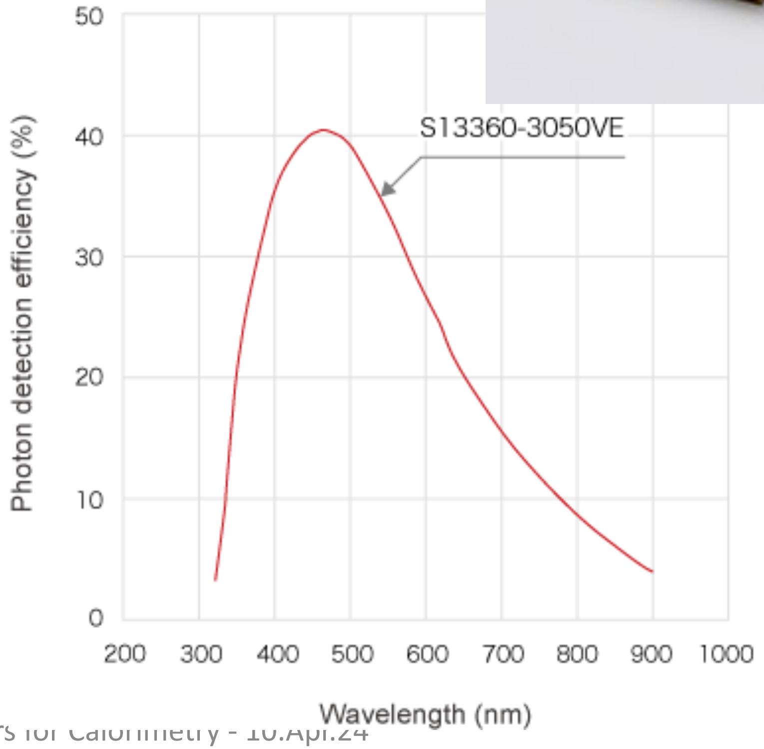


MPPC Arrays - Useful for Dual Readout, SpaCal, MAXICC

MPPC S14160/S14161
50µm pixels

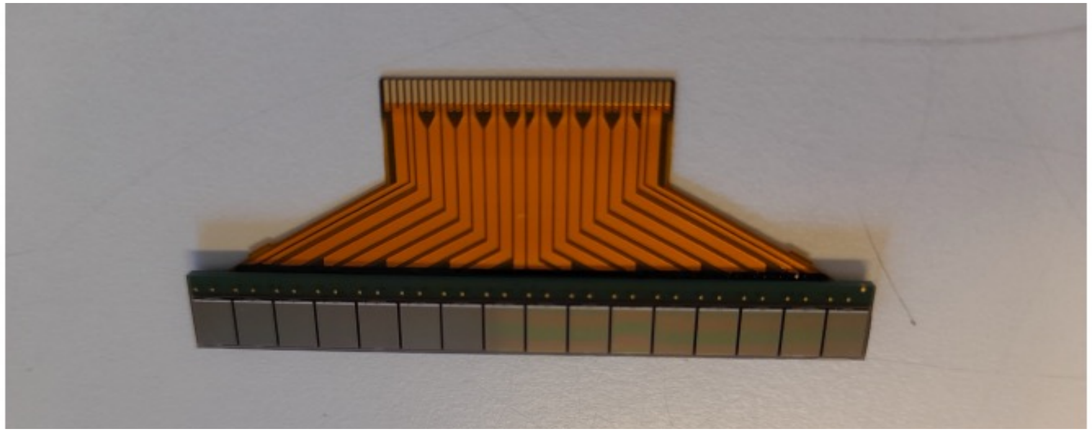


MPPC S13360/S13361/S13363
25, 50µm, 75µm pixels



SiPM with Thermo Electric Cooling (TEC) developed for CMS BTL (1x16) SiPM arrays, from initial concept development through RADiCAL. Tested in environment with high 2 x 10^{14} n/cm^2 background.

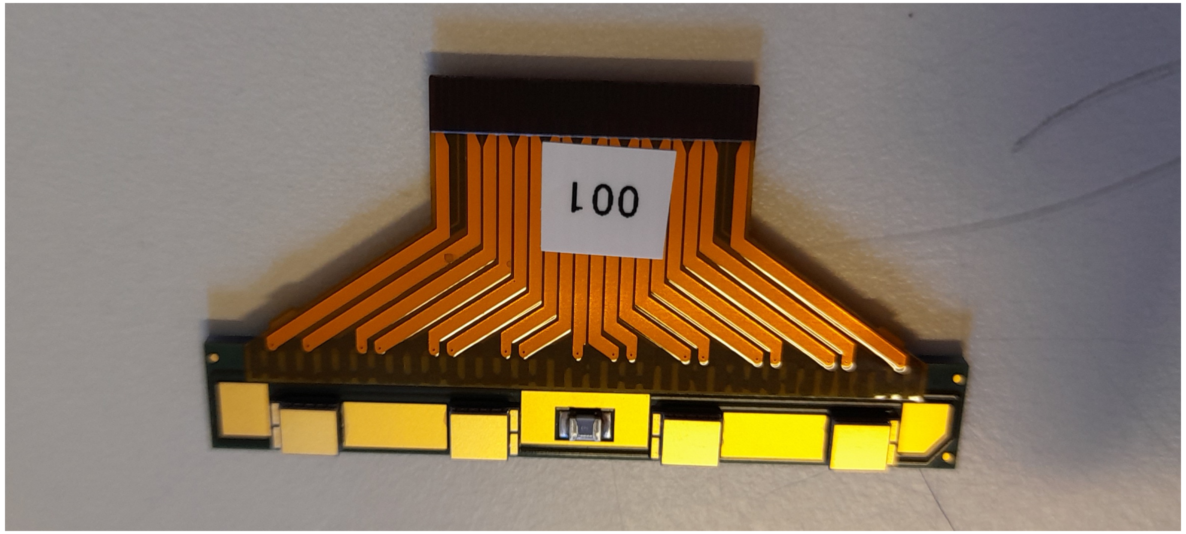
CMS BTL Array (1x16 sensor array)



Operate TEC with forward current to reduce SiPM temp by -20c below CO_2 cooling (to -45c).

Operate TEC in reverse current up to 50c to thermally anneal SiPM during beam off periods.

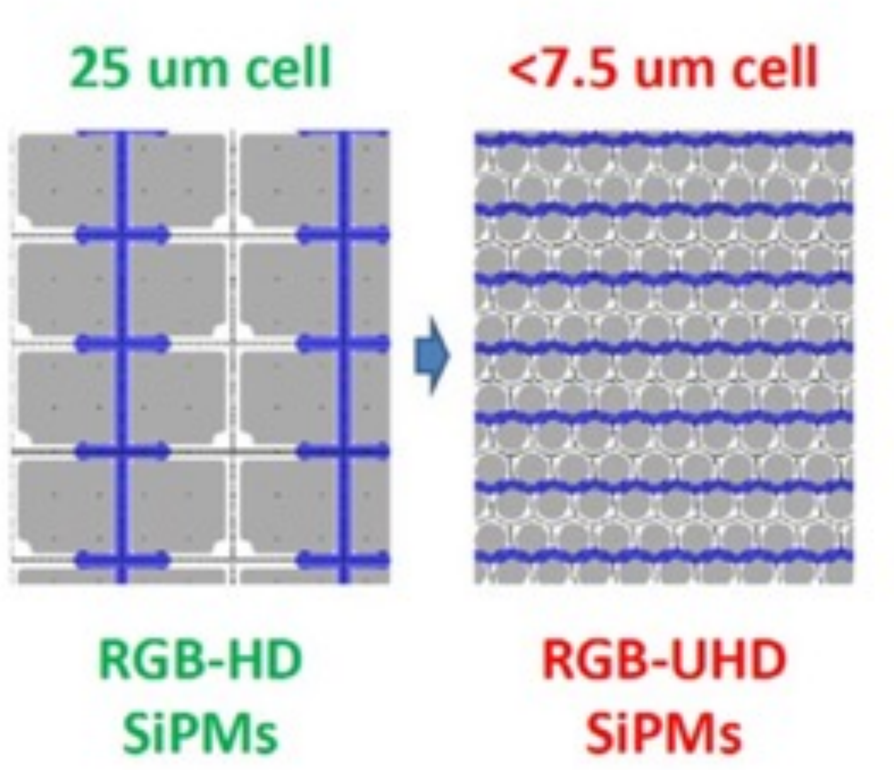
CMS BTL Array (backside with TEC)



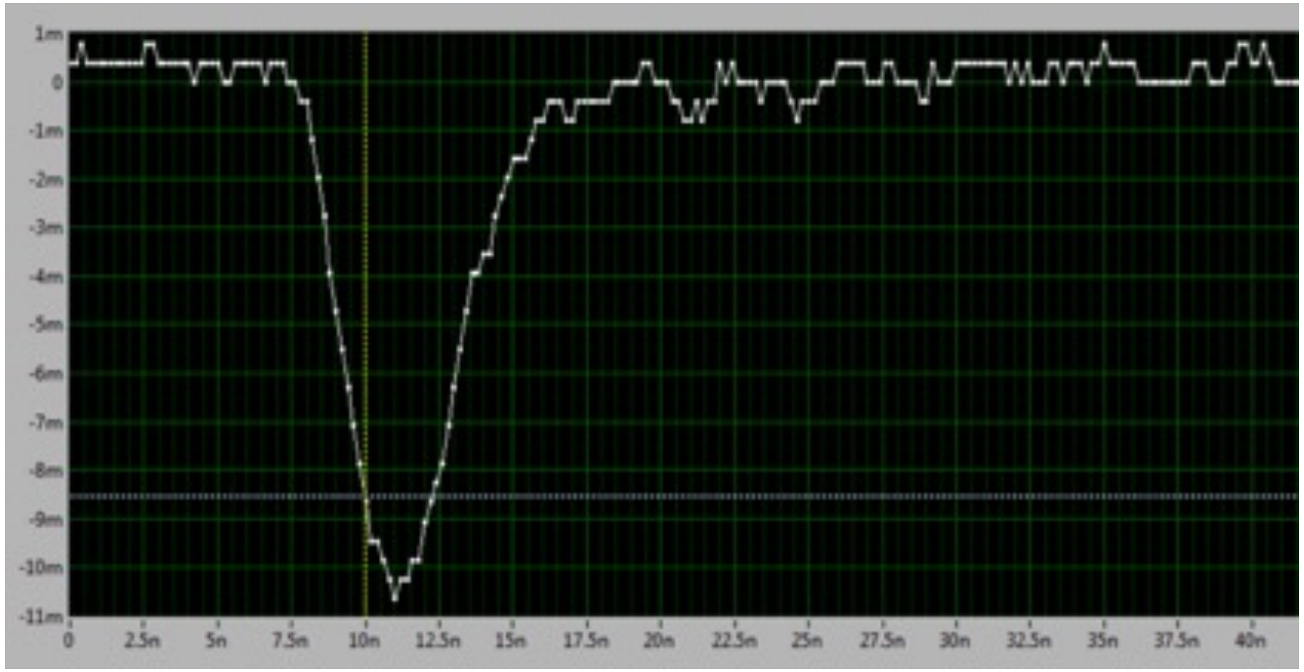
A. Heering et al, “Integration of mini TECs on the CMS BTL 16 ch SiPM array to reduce the DCR after very high irradiation”, NDIP20.

FBK SiPM development for RADiCAL
(arXiv:2203.12806) for fast timing, avoid saturation

Format to reduce boundary regions between SiPM pixels



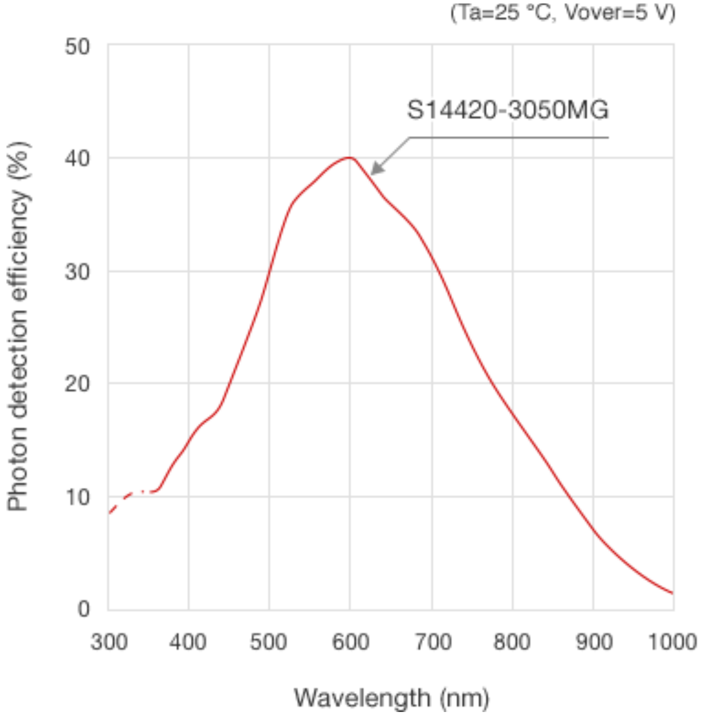
Pulse from a FBK SiPM with 5μm pixels. Horizonal scale division is 2.5ns.



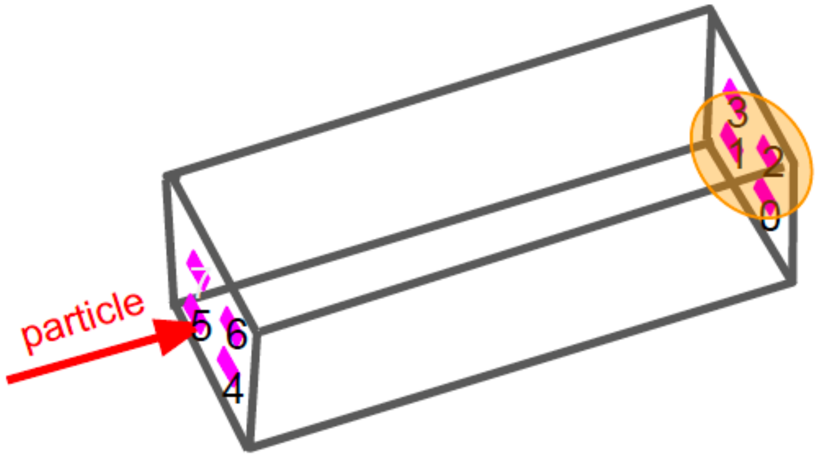
MPPC: Longwave visible, near IR - beneficial for new material studies, and signal separation strategies…

MPPC S1442/S14422

25μm, 50μm pixels



A $PbWO_4$ Crystal

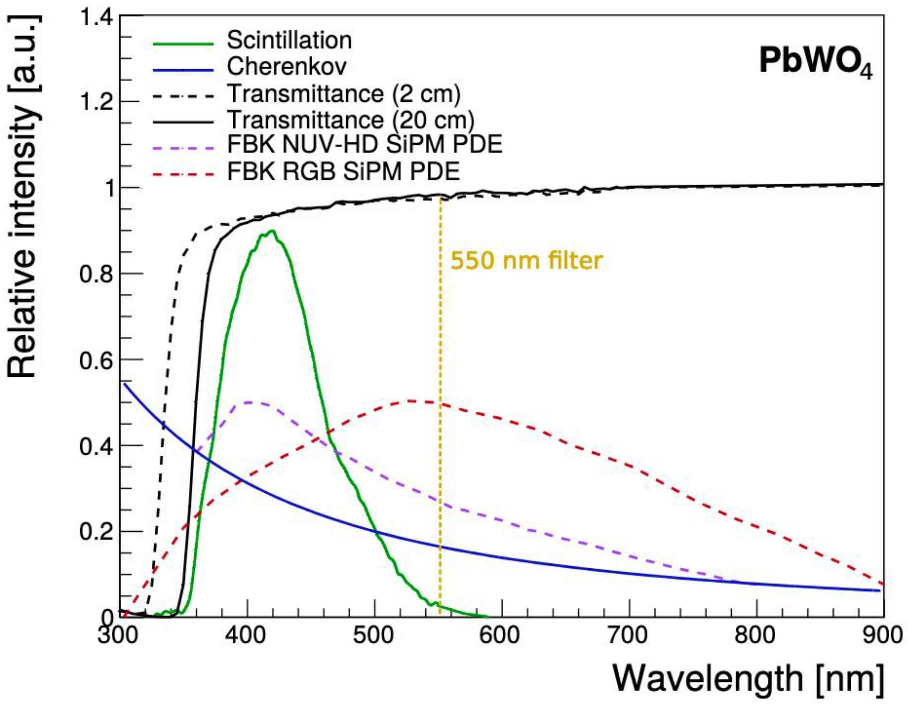


SiPM + filtering for separation of Scintillation and Cherekov light in crystals.

$PbWO_4$: Separating Cherenkov signal from scintillation signal crystals

- Usual approach
  - Detect Cherenkov at short wavelengths
  - Detect scintillation at long wavelengths
- MAXICC/Calvision are studying an inversion of that approach for crystal calorimetry.

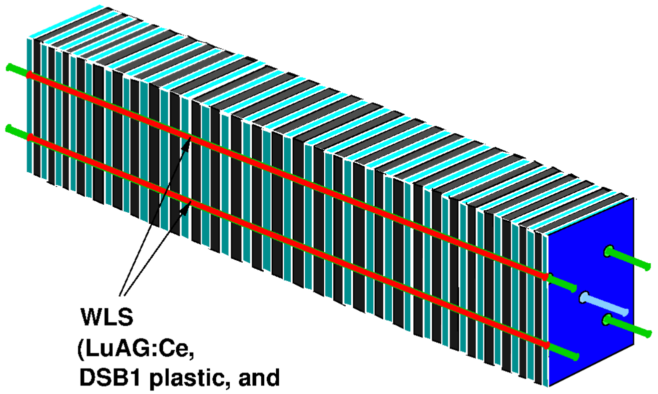
Wavelength properties, scintillation crystal, optical filter and FBK SiPM

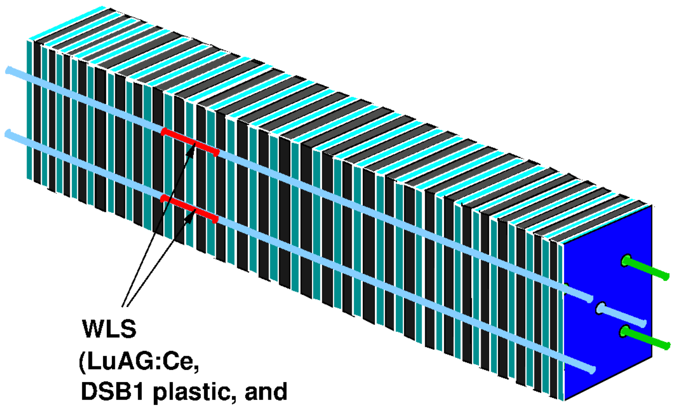


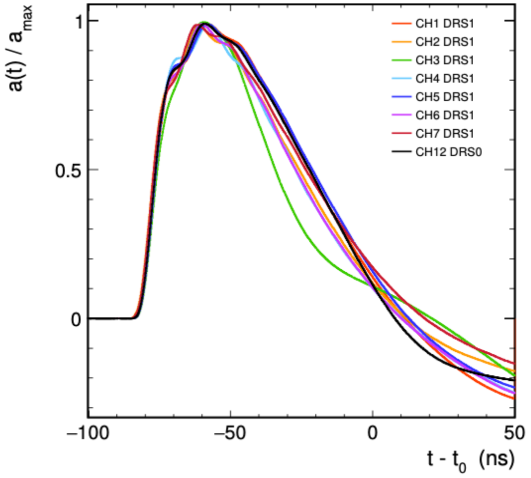
SiPM signals and front electronics/DAQ

RADiCAL example, using WLS capillaries

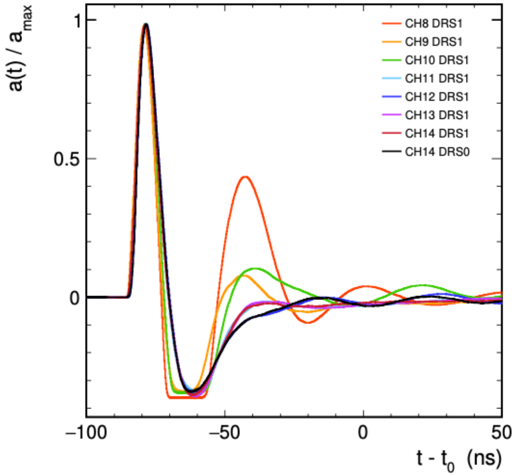
Energy resolution - detect full EM shower - low gain signals







Low gain for energy and position



High gain for timing

Position and Timing resolution - selected locations in EM shower depth. Position uses local energy deposition

High and Low gain signals needed.

Some features of PMTs

Benefits

- High gain/bandwidth
- Low noise
- Fast response for both timing and energy
- QE depends on photocathode and/or faceplate material
- Operation possible over a wide range of temperatures
- Radiation tolerant

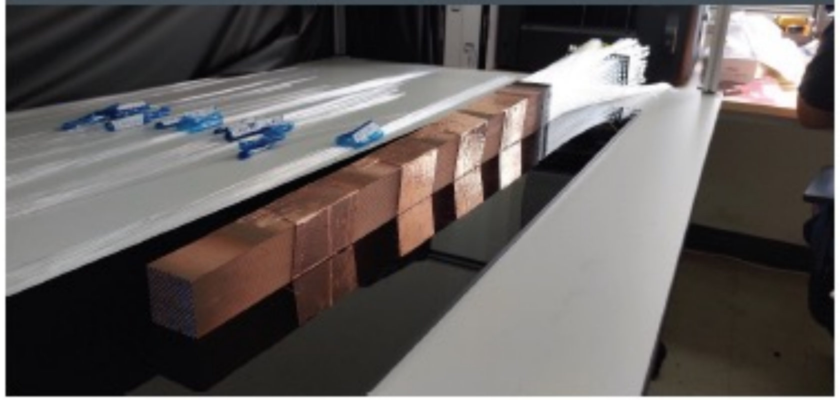
Challenges

- Magnetic Field (may/may not be an issue)
- Physical Dimensions
- Unit cost
- Lifetime

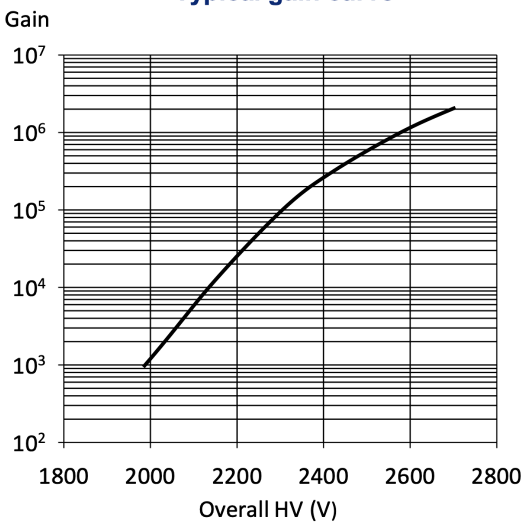
MCP-PMT for DRCAL

Model	Effective Area	Rise Time [ns]	Max V [V]
PLANACON XP85112	53 mm × 53 mm (8 × 8 cells)	0.5	2800
PLANACON XP85012		0.6	2400

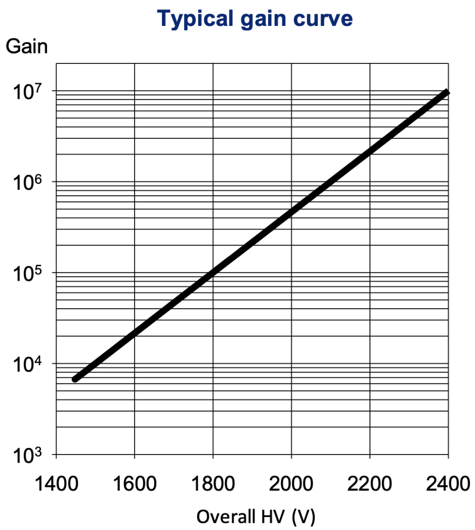
3D printing module



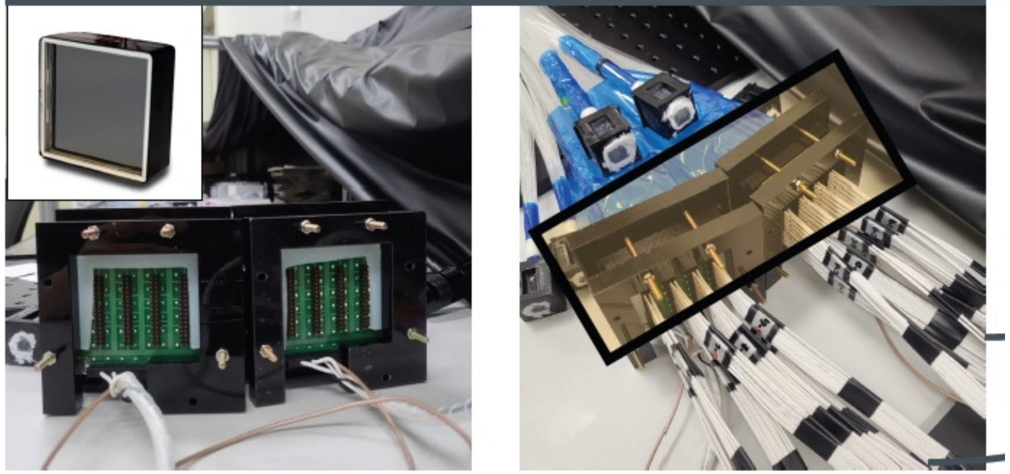
XP85112 (Scifi)



XP85012 (Cherenkov)



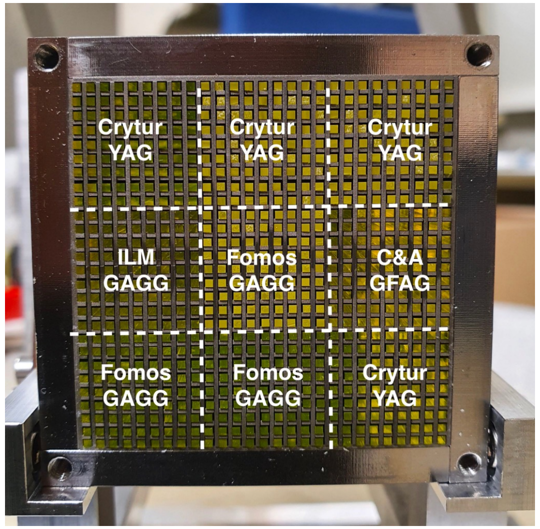
Readout side of 3D printing module



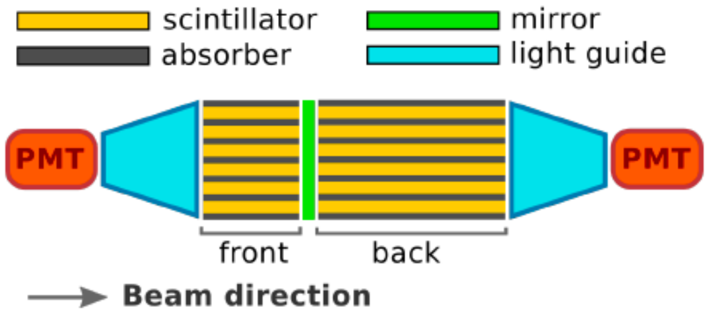
Haeun Jang (Yonsei Univ) 2023 KPS Fall Meeting

Objective: To use timing to locate shower depth

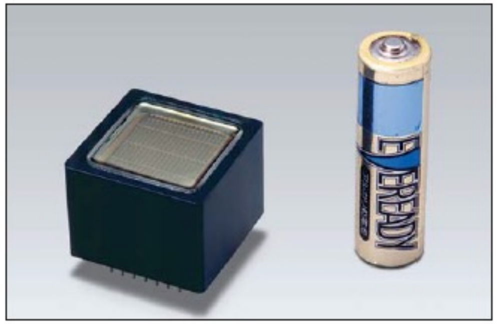
MCD-PMT for LHCb



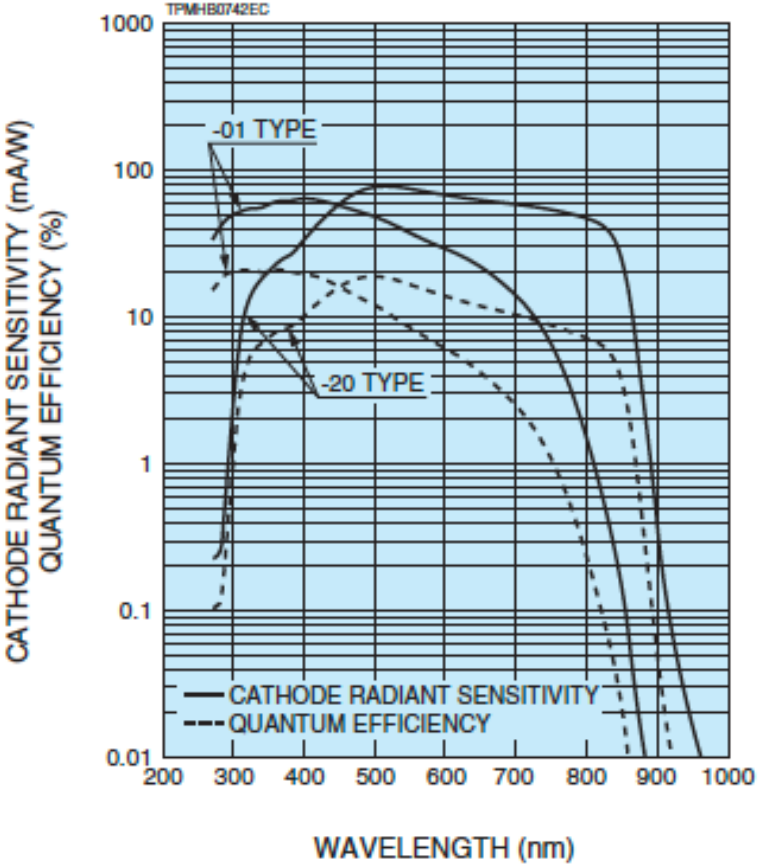
Garnet/Tungsten SPACAL
P. Roloff, EPS 2021

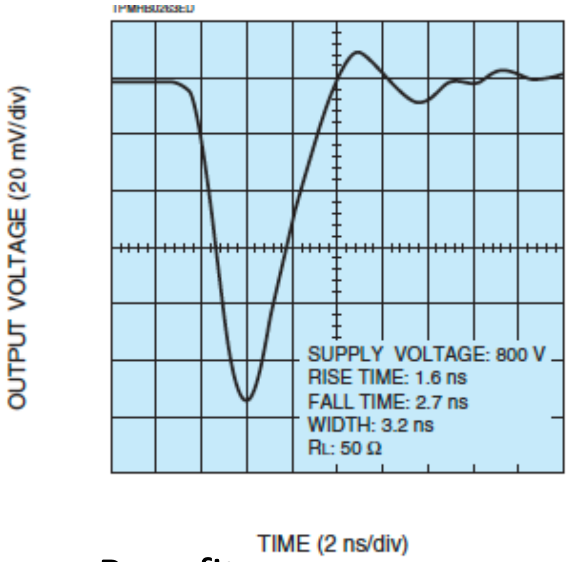


DESY: Electron beam energy up to 5 GeV.
Using: R7600U-20, ~20psec time resolution
Using: R12421 , 10%/sqrt(E) constant term for beam angle θx, θy = 3º



Some characteristics of R7600U-20 MCD PMT





Benefit:
Fast, effient, room temperature.

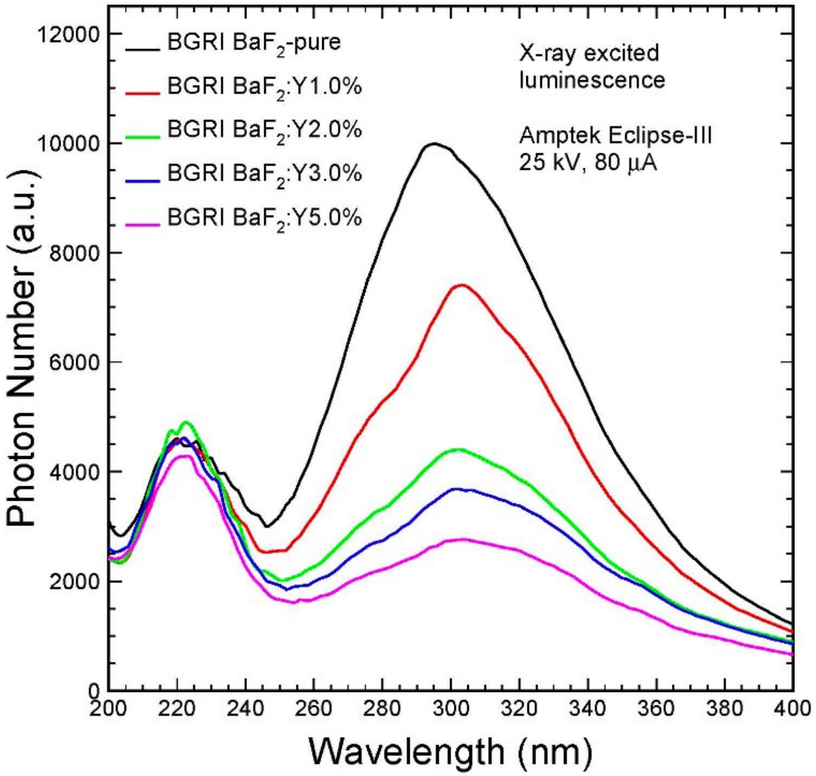
The fast component of BaF_2 - ongoing challenge…

Chen Hu, Liyuan Zhang, Ren-Yuan Zhu et al., Development of Yttrium-Doped BaF2 crystals for Future HEP Experiments, IEEE TNS Nucl. Sci. 66 (2019) 1854-1860

Ba:F_2 has UV emission with two components, one very fast, one slow

- Two approaches to attempt to deal with this:
- Co-doping of BaF_2 with Yttrium.
  - Suppresses slow component.
  - Preserves the fast component.
- Developing solar-blind photosensors to selectively detect the fast component emission

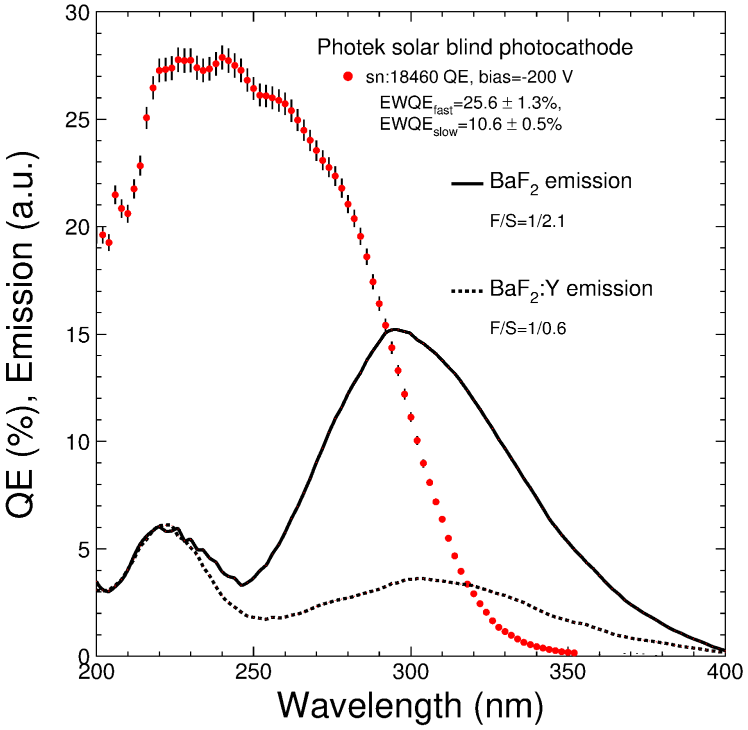
BaF_2:Y emission



Associated Photosensor R&D

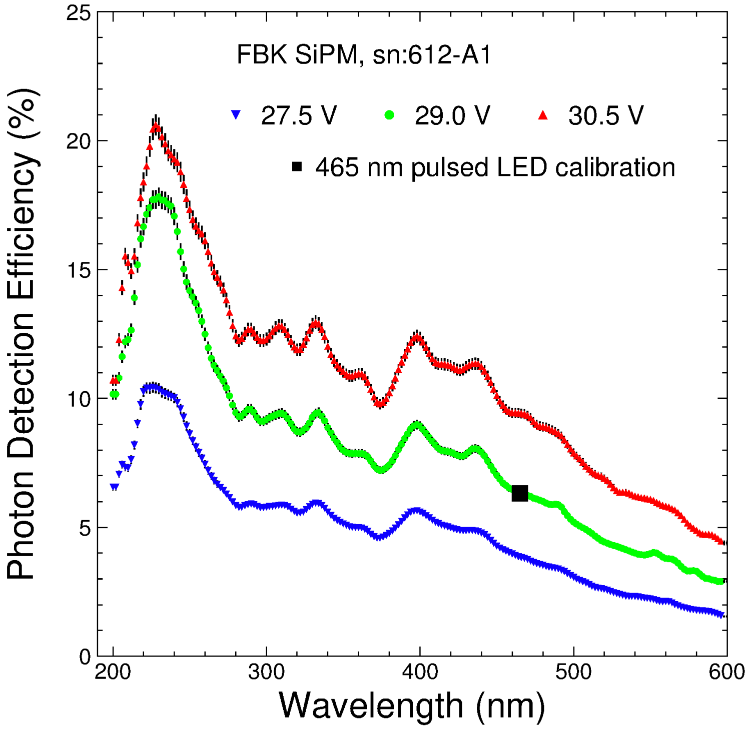
L. Zhang, et al, "Spectral Response of UV Photodetectors for Barium Fluoride Crystal Readout", IEEE Trans on Nucl. Sci, Vol 69, No.4, April 2022

Search for a specialized Solar Blind PMT - Photek sn 18460



Search for a specialized UV SiPM

FBK SiPM, sn612-A1



Summary

- Great opportunities for R&D where the various projects within WP3 can collaborate and learn from each other as well as other DRDs.
- Work will need to be brought to bear that includes:
  - Optical Media
  - Photosensors: SiPM, SiPM Arrays, MCD-PMT, MCP-PMT, and others
  - Electronics/DAQ
  - Simulation
  - Beam testing
- Among the goals are the development of new approaches in optical calorimetry that could emerge during this formative period of collaboration.

Extra…

Digital SiPM: dSiPM

- A commercial vendor is Phillips
- Each SiPM pixel has:
  - Its own companion quench and recharge circuitry.
  - One bit memory to allow read or block.
  - Cells can be added up digitally
  - Aimed in part for medical applications
- Some issues:
  - The radiation hardness of devices
  - Noise.
  - Cryogenic application?
  - Further discussion with DRD4 needed for further understanding.