Progress on a SiPM for readout of the fast component of BaF_2 scintillation light

David Hitlin

CPAD Workshop

November 8, 2023

Motivation

- Barium fluoride is an attractive inorganic scintillator for high rate, high time resolution experiments in HEP and PET

Parameter:	ρ	MP	$X_0{}^*$	$R_M{}^*$	dE/dx^*	$\lambda_I{}^*$	$\tau_{\rm decay}$	$\lambda_{\rm max}$	$n^\dagger$	Relative output‡	Hygro-scopic?	$d(\mathrm{LY})/dT$
Units:	g/cm^3	°C	cm	cm	MeV/cm	cm	ns	nm				%/°C§
NaI(Tl)	3.67	651	2.59	4.13	4.8	42.9	245	410	1.85	100	yes	−0.2
BGO	7.13	1050	1.12	2.23	9.0	22.8	300	480	2.15	21	no	−0.9
BaF_2	4.89	1280	2.03	3.10	6.5	30.7	650^s	300^s	1.50	36^s	no	-1.9^s
							$<0.6^f$	220^f		4.1^f		0.1^f
CsI(Tl)	4.51	621	1.86	3.57	5.6	39.3	1220	550	1.79	165	slight	0.4
CsI(Na)	4.51	621	1.86	3.57	5.6	39.3	690	420	1.84	88	yes	0.4
CsI(pure)	4.51	621	1.86	3.57	5.6	39.3	30^s	310	1.95	3.6^s	slight	−1.4
							6^f			1.1^f		
$PbWO_4$	8.30	1123	0.89	2.00	10.1	20.7	30^s	425^s	2.20	0.3^s	no	−2.5
							10^f	420^f		0.077^f		
LSO(Ce)	7.40	2050	1.14	2.07	9.6	20.9	40	402	1.82	85	no	−0.2
PbF_2	7.77	824	0.93	2.21	9.4	21.0	-	-	-	Cherenkov	no	-
CeF_3	6.16	1460	1.70	2.41	8.42	23.2	30	340	1.62	7.3	no	0
$LaBr_3$(Ce)	5.29	783	1.88	2.85	6.90	30.4	20	356	1.9	180	yes	0.2
$CeBr_3$	5.23	722	1.96	2.97	6.65	31.5	17	371	1.9	165	yes	−0.1

Motivation

- Barium fluoride is an attractive inorganic scintillator for high rate, high time resolution experiments in HEP and PET, provided there is an adequate photosensor
  - Y doping can improve the fast/slow ratio
  - Photosensor requirements
    - Extended UV response
    - High sensitivity to the fast (<0.6ns) scintillation component at 220 nm
    - Low sensitivity to the larger slow (650 ns) component at 300 nm
    - Protection from damage to Si due to incident UV scintillatior normal ionizing radiation dose we normally consider)
    - Works in a magnetic field
    - Adequate dynamic range and time response
  - This talk summarizes our efforts to develop such a photosensor

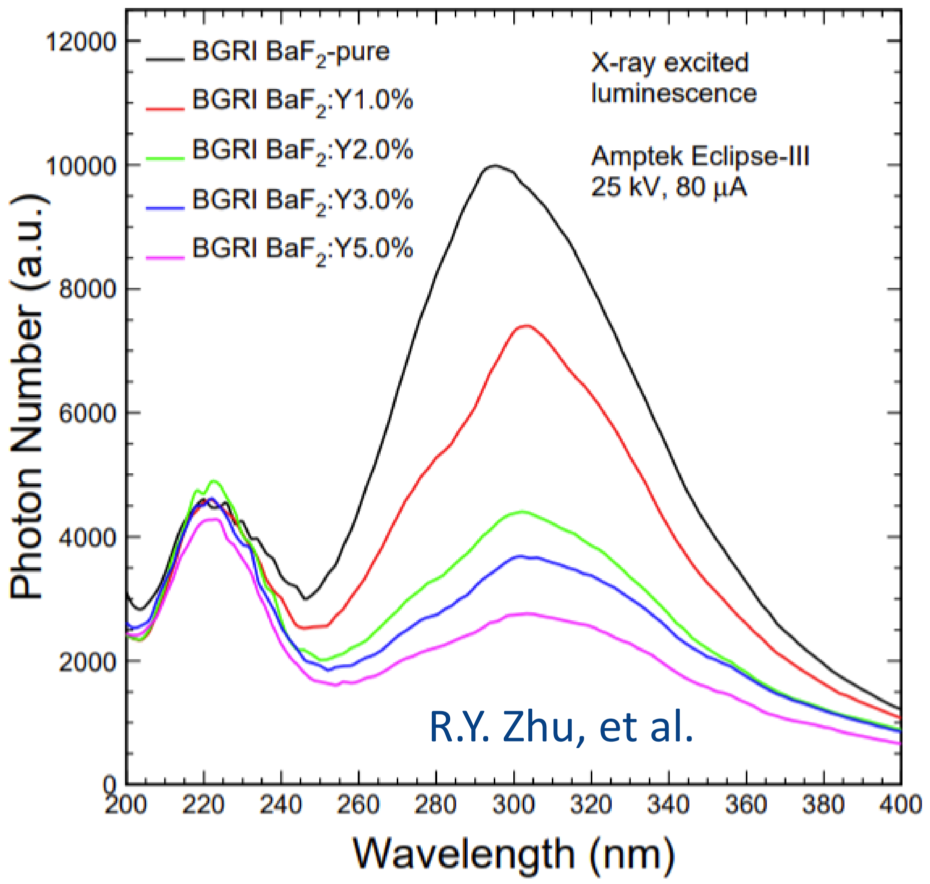
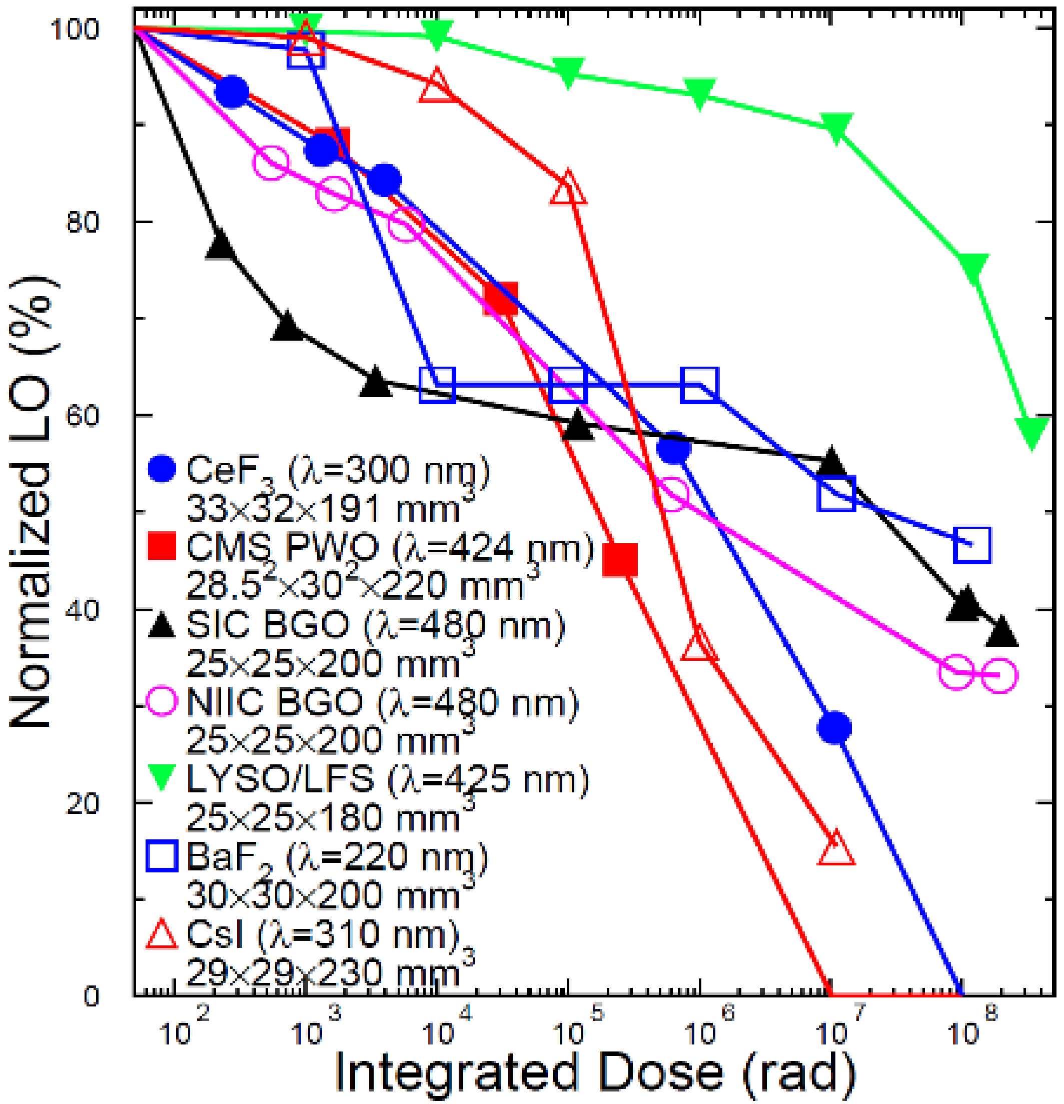
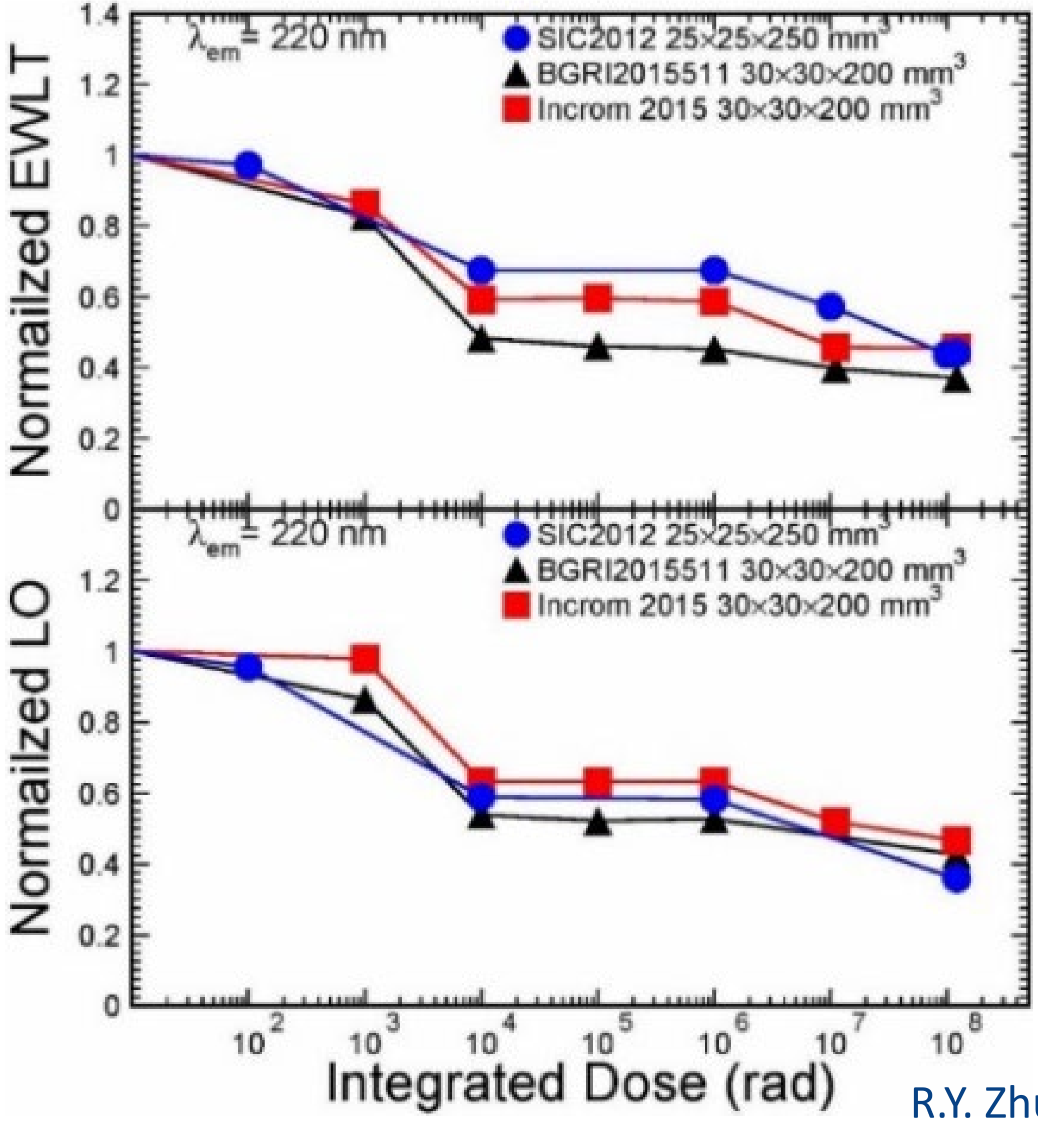


FIG. 20. X-ray excited emission spectra measured for BGRI BaF_2 crystal samples with different yttrium doping level.

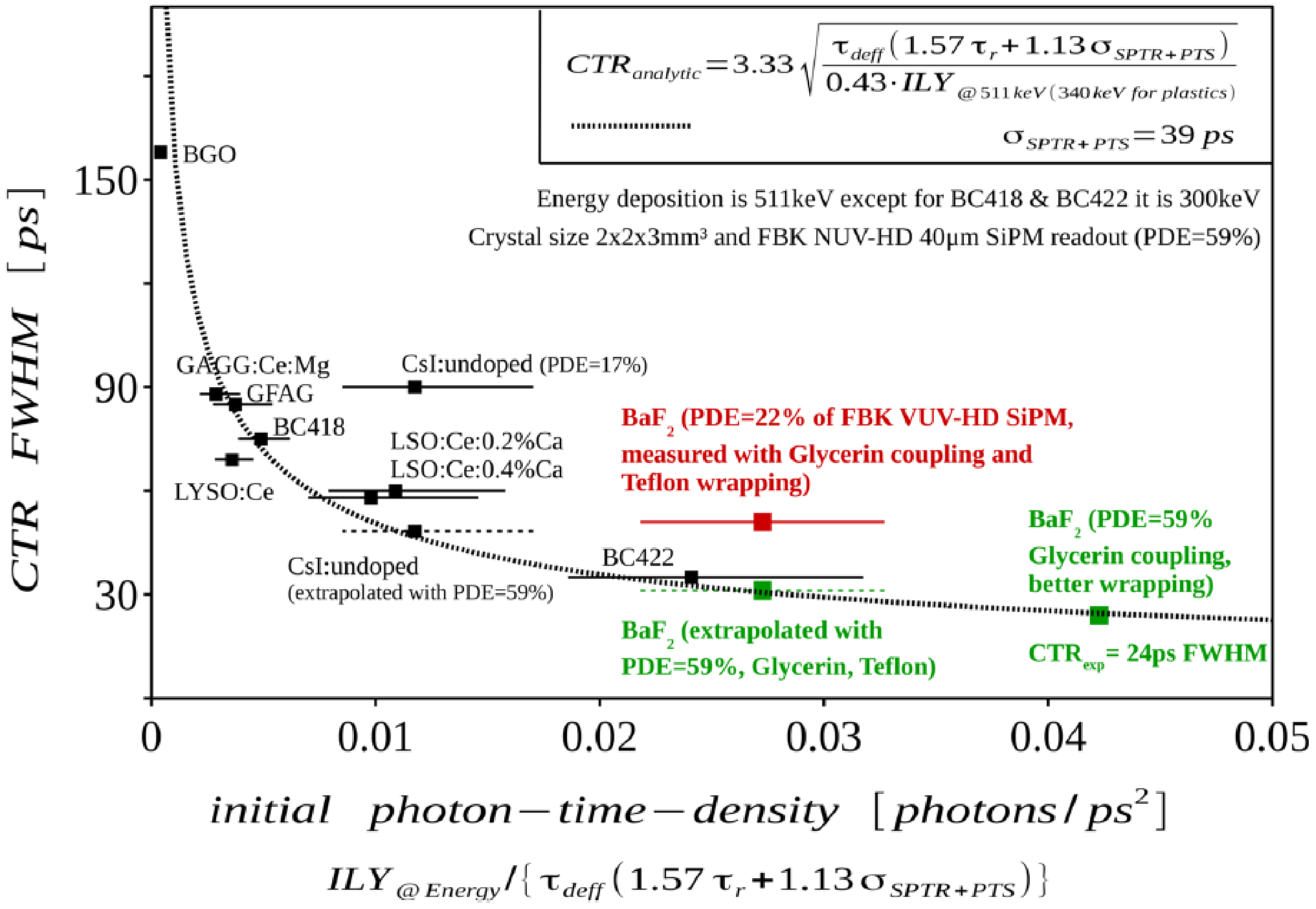
Light output vs ionizing radiation dose





R.Y. Zhu, et al.

BaF_2 is capable of excellent time resolution

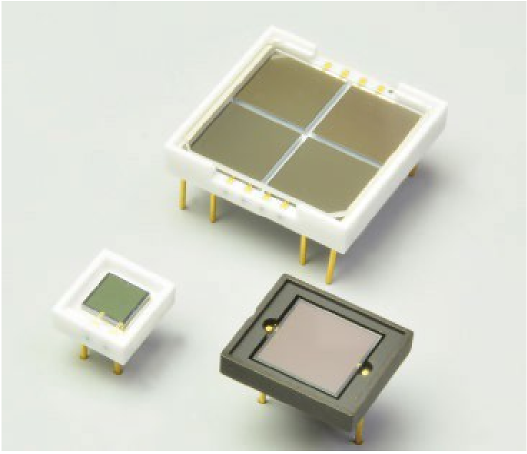


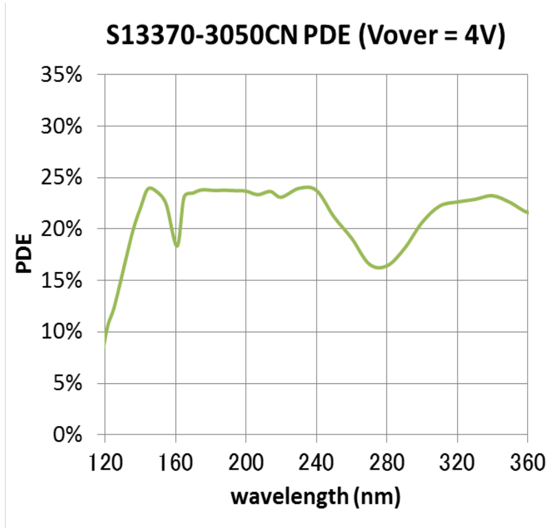
S. Gundacker et alPhys. Med. Biol. 66 (2021) 114002

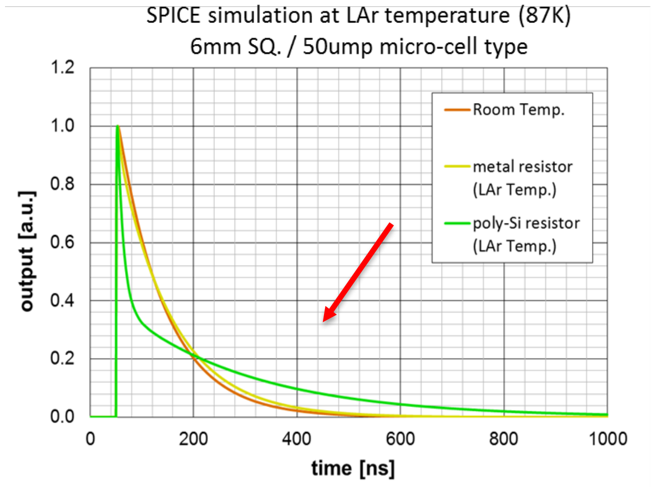
Hamamatsu and FBK produce extended UV SiPMs

<u>S13370 series</u>

- High PDE in VUV wavelength range
- Works with LXe @ 175 nm or LAr @ 128 nm
- No slow/fast component discrimination
  - Relevant to BaF_2
- Typical decay time of a large area device, dictated by RC time constant
- 4@ 6x6mm
- Works at cryogenic temperatures
- Subject to damage from incident UV scintillation light



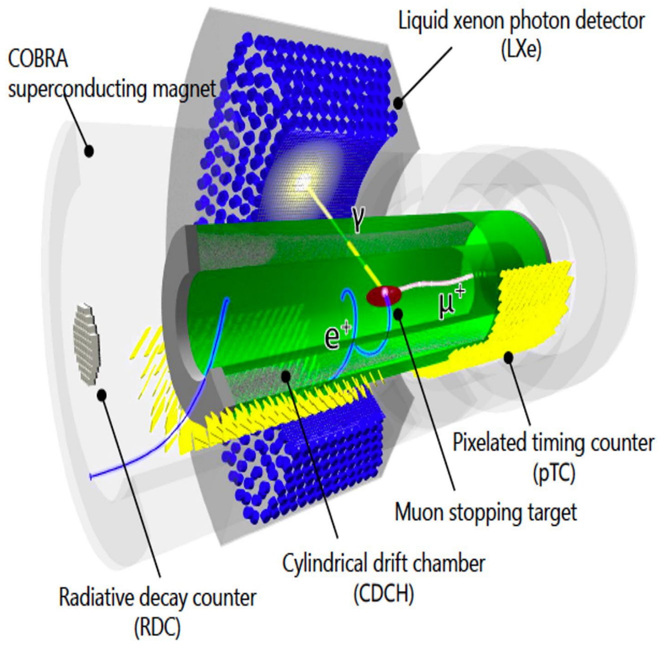


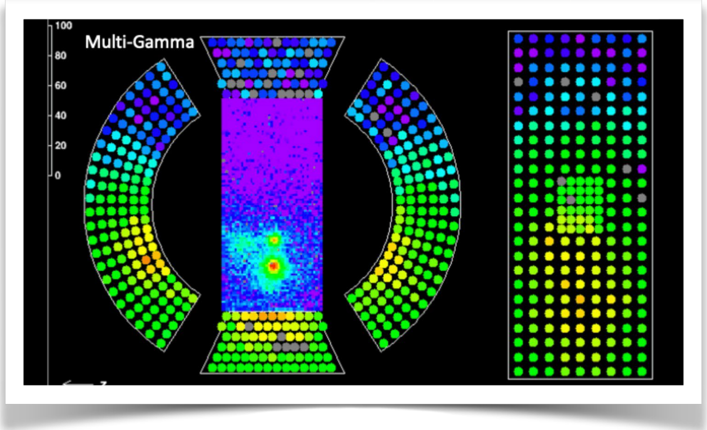


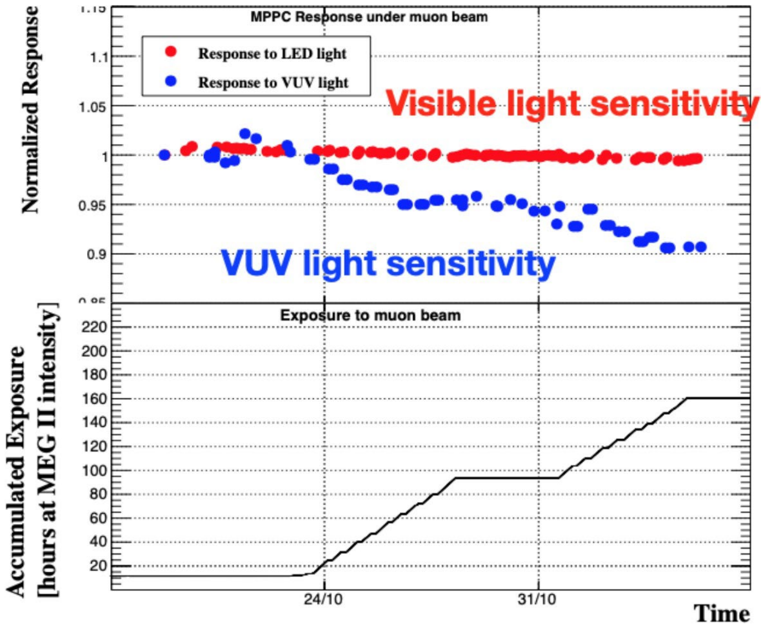
Series/parallel connection of 6x6 mm SiPMs, as in MEG-II and the current Mu2e calorimeter, improves decay time characteristics

FBK also has excellent VUV SiPMs

MEG-II - The LXe Calorimeter







They observe a degradation of the PDE of the MPPCs under beam conditions

Successfully developed a recovery procedure, to be repeated periodically (annealing: let the MPPCs draw a large current when illuminated by LEDs, so to heat them by the Joule effect up to 70 ºC for several hours)

Francesco Renga - DISCRETE2021, B

Degradation speed ~0.08%/hour

MEG-II Annealing

MPPC PDE Degradation

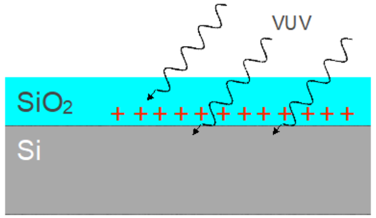
- Possible cause = "surface damage by VUV-light"

  Electron-hole pair generated in SiO_2

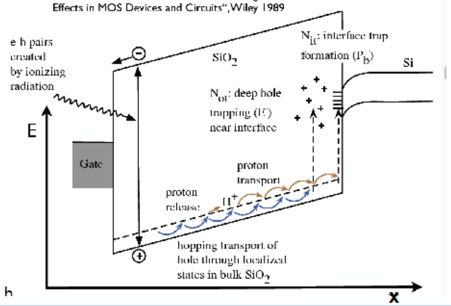
  →Holes are trapped at interface SiO_2 - Si

  →Accumulated positive charge will reduce electric field near Si surface, which reduces the collection efficiency of charge carrier

  - Note that charge carrier generated within 5nm at Si surface for VUV
- Similar phenomena are known for UV photo diode
  - But degradation happens only with much higher amount of light at room temp.
  - Degradation saturated at certain level
- Still to be understood
  - It seems that the degradation is enhanced at low temperature
  - Degradation can saturate?



from T.P. Ma and Paul V. Dressendorfer, „Ionizing Radiation Effects in MOS Devices and Circuits", Wiley 1989



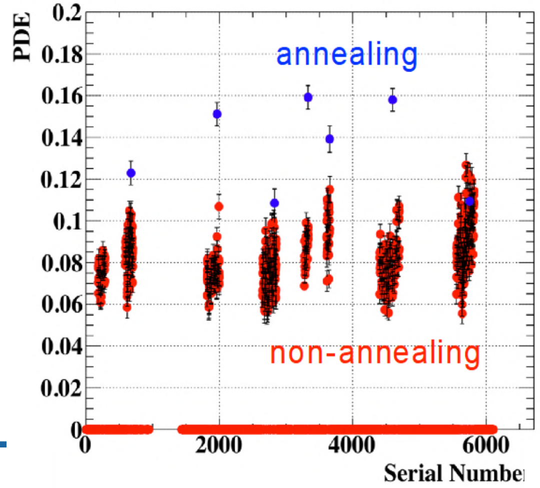
W.Ootani, "*Liquid Xenon Photon Detector with Highly Granular Scintillation Readout fo*

Possible Solution

- Annealing was done for several sensors without opening the detector
  - Heating MPPC with large sensor current □24mA with LED light illumination
  - Maximum annealing @T~60°C, 40hr
- Almost fully recovered by annealing!
  - Recovery up to by 70%
- Implementation is, however, not straightforward…
  - Annealing can be done only at room temp without LXe
  - Ideally done during accelerator shutdown period

    →We have to survive for one year at least
  - N.B. maximum PDE is not necessary to reach design detector performance

MPPC	Current [mA]	Time [hr]	PDE [%] 2018	PDE [%] 2019	Recovery
2763	20	22	7.9	9.8	1.24
2672	19-20	23	10.4	12.8	1.23
2802	17-19	23	9.1	11.5	1.26
2712	19	23	9.4	10.3	1.1
2789	19-24	38	9.5	13.8	1.45
2700	20-24	38	10.0	15.7	1.57
2658	21-24	38	8.8	15.3	1.74



W.Ootani, "*Liquid Xenon Photon Detector with Highly Granular Scintillation Reado*

What is required for BaF_2 readout is fast/slow discrimination and UV radiation hardness

The challenge

- Can we develop a photosensor that efficiently sees the fast UV scintillation component while being insensitive to the slow component?
- Works in a magnetic field
- At high intensities is not damaged by the scintillation light itself

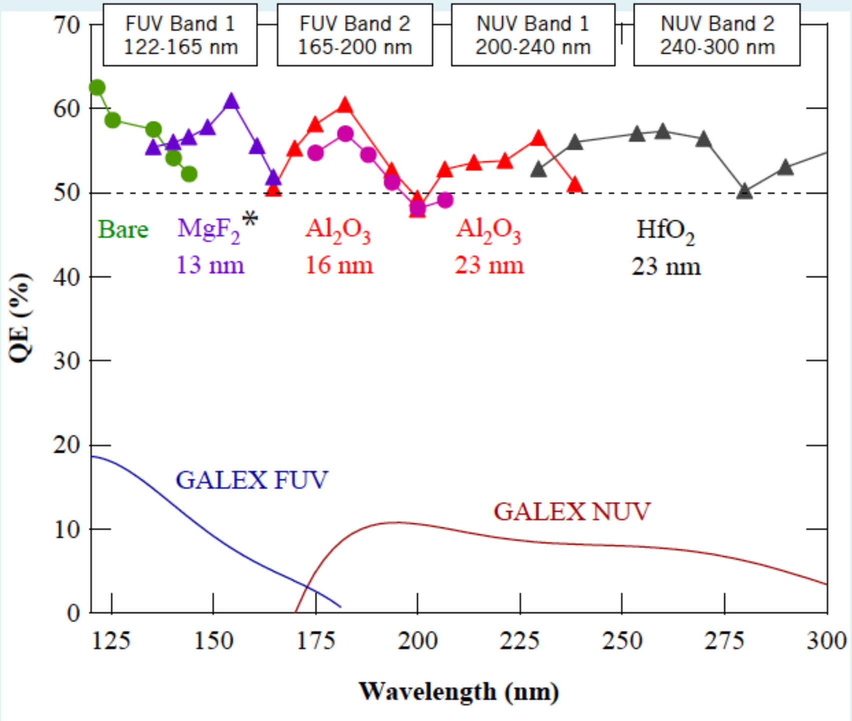
- Based on our previous development of a large area APD with JPL and RMDinc, we have undertaken to develop a SiPM with the needed characteristics

- Caltech: D. Hitlin, J. Oyang, J. Trevor
- JPL: J. Hennessy, M. Hoenk, A. Jewell
- FBK: A. Ficorella, A. Gola, G. Paternoster

- Integrated ALD filter for well-defined bandpass and high efficiency
- Delta-doped MBE layers for robustness and improved timing
- Back-illumination

ALD antireflection filters improve QE

AR Coatings for UV Detectors



*MgF_2 result for thermally evaporated film

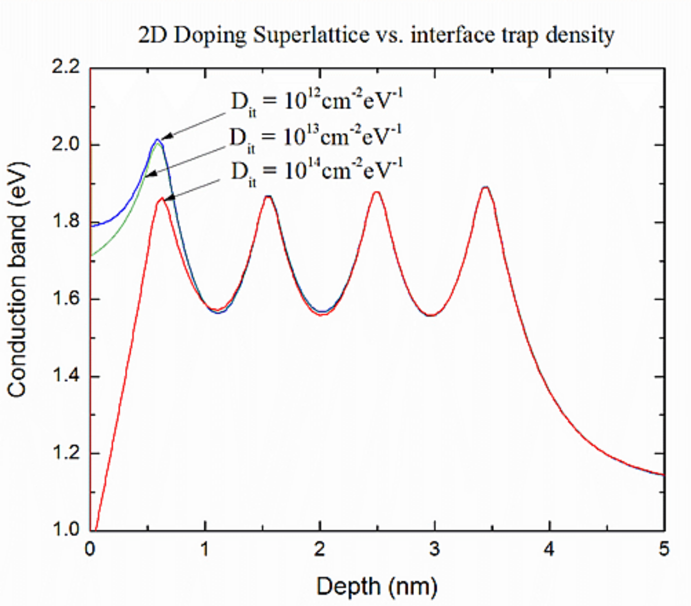
ALD-AR coatings provide up to **2X improvement** over uncoated baseline and a **5x-50x improvement** over incumbent UV detector technology

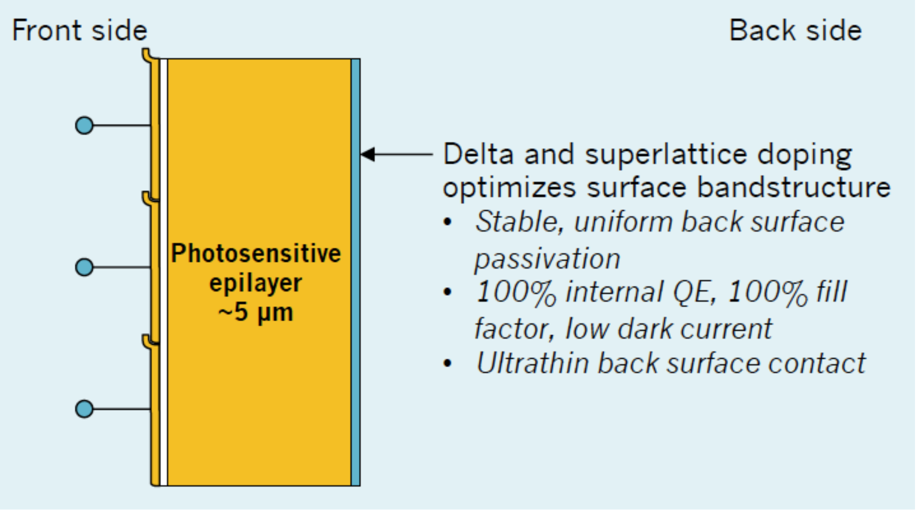
Nikzad, *et al.*, *Applied Optics*, **51**, (2012) 365.

This ALD technique can be used to make a sophisticated internal bandpass filter

Delta-doped superlattice structures

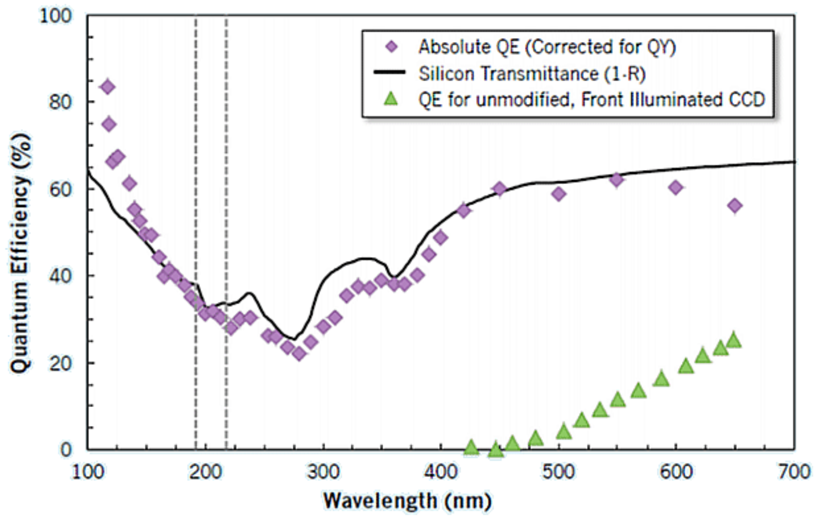
- JPL has developed superlattice (delta-doped) structures that provide enhanced quantum efficiency and improved time response for photosensors
  - Delta-doped superlattices have been successfully employed for many years to enhance the UV performance of CCDs and APDs used in UV astronomy in satellites and balloons
- Monoatomic layers of boron are implanted beneath the photosensitive surface of the SiPM using molecular beam epitaxy (MBE) (2D doping) and SiO_2 layers are then grown
- The MBE layers allow the conduction band to remain stable with varying surface charge



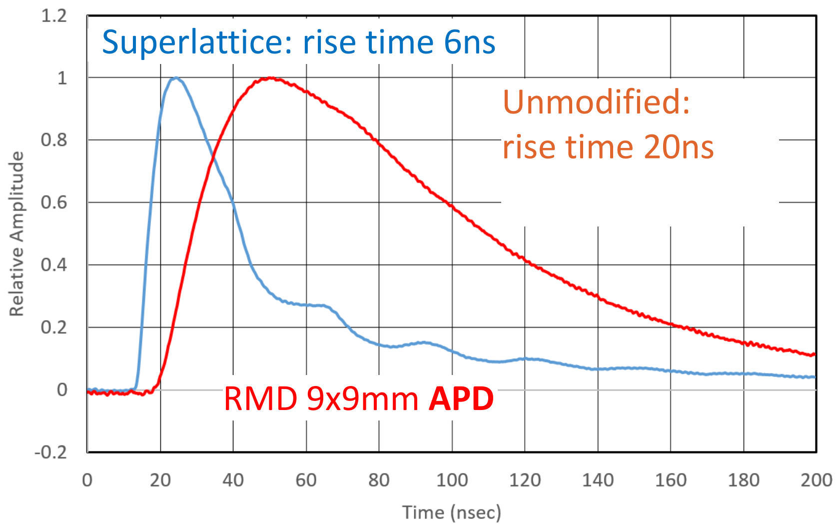


Delta doping

- ❑ Improves quantum efficiency
  - ❑ Recombination of photoelectrons is suppressed by quantum exclusion, resulting in close to **100% internal QE**
  - ▪ Quantum efficiency in the 200-300 nm region approaches the silicon transmittance (1-R) limit

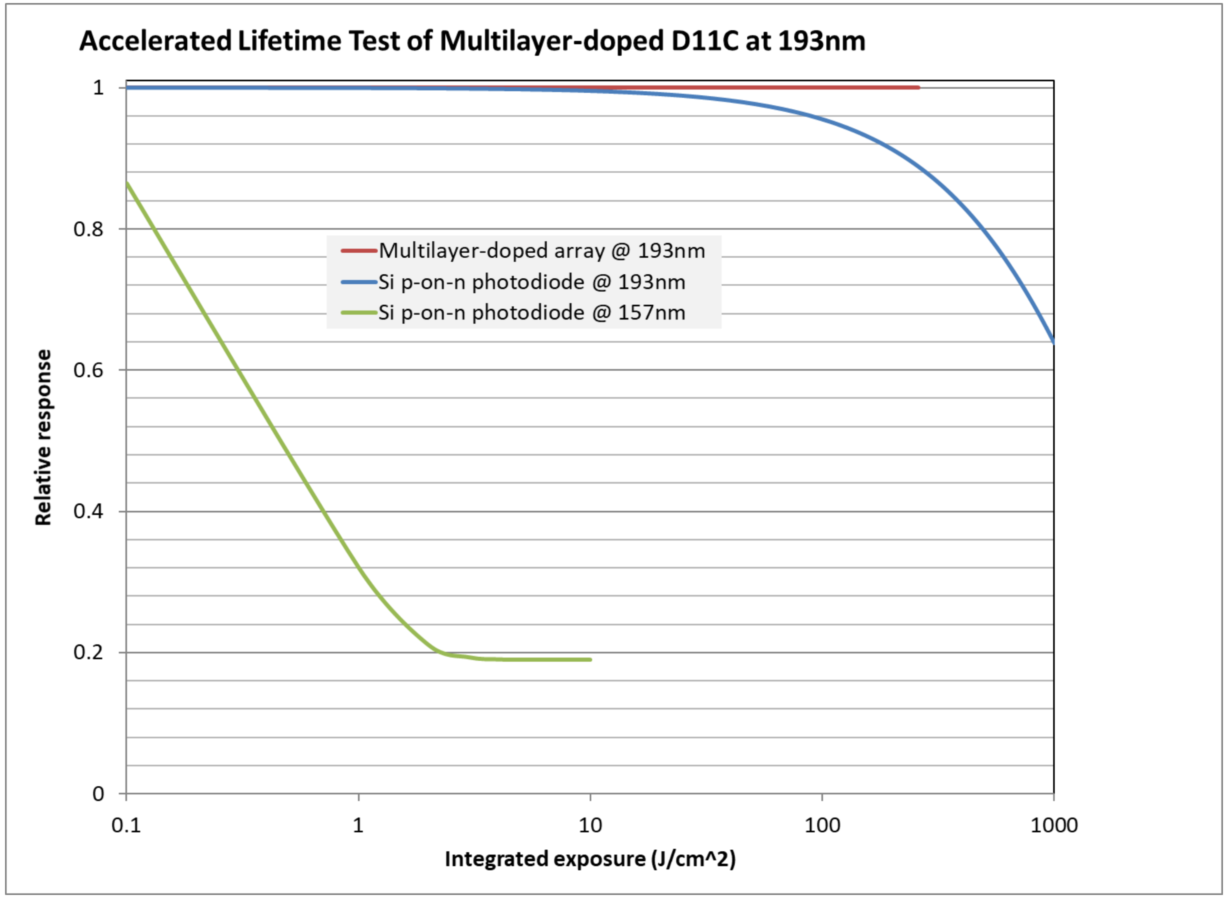


- ❑ Improves rise time and decay time
  - ❑ Elimination of the undepleted region before the avalanche structure **substantially improves time performance** over a normal 9mm RMD APD
    This should also work with a SiPM structure



Delta-doping protects against UV damage

- The superlattice structure provides **stability under intense UV illumination (The MEG-II problem)**
  - Relevant regime for Mu2e-II is ~ .1-10 J/cm^2 of 200 -300 nm UV (~ 4-6 eV)
  - Note that Y-doping of BaF_2 substantially reduces the amount of UV radiation reaching the SiPM
- This motivates us to make a SiPM with a superlattice structure



U. Arp *et al.*, J. Elect. Spect. and Related Phenomena, **144**, 1039 (2005)

CIT/JPL/FBK SiPM - a phased approach

- Develop a SiPM with an integrated filter for readout of BaF_2 fast component
- Building on our experience with a large area APD developed with RMD, we have adopted a phased SiPM development approach

DONE
1. Build a **three-layer ALD filter** on a 6x6 mm NUV SiPM structure, exploring different SiNx passivation layers, guard ring structures, …
2. Fabricate **2x3 arrays of the 6x6 mm chips**, biased in series parallel configuration à la MEG and Mu2e to read out larger crystals

DONE
3. Improve slow component rejection with more sophisticated **five-layer filters**

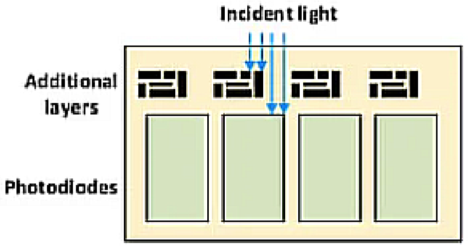
4. Use **delta doping** and **backside illumination** to improve PDE, effectiveness of the filter, timing performance and UV tolerance

DONE
- Explore diode structures of various sizes to pinpoint source of leakage current

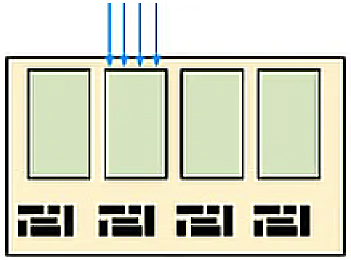
Underway
- Explore MBE recipes for producing delta-doped layers

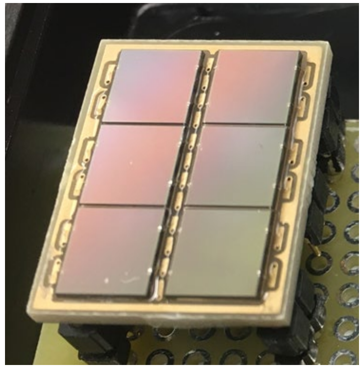
Not funded
- Fabricate back-illuminated SiPMs with a five-layer filter and delta-doping

Front illuminated



Back illuminated

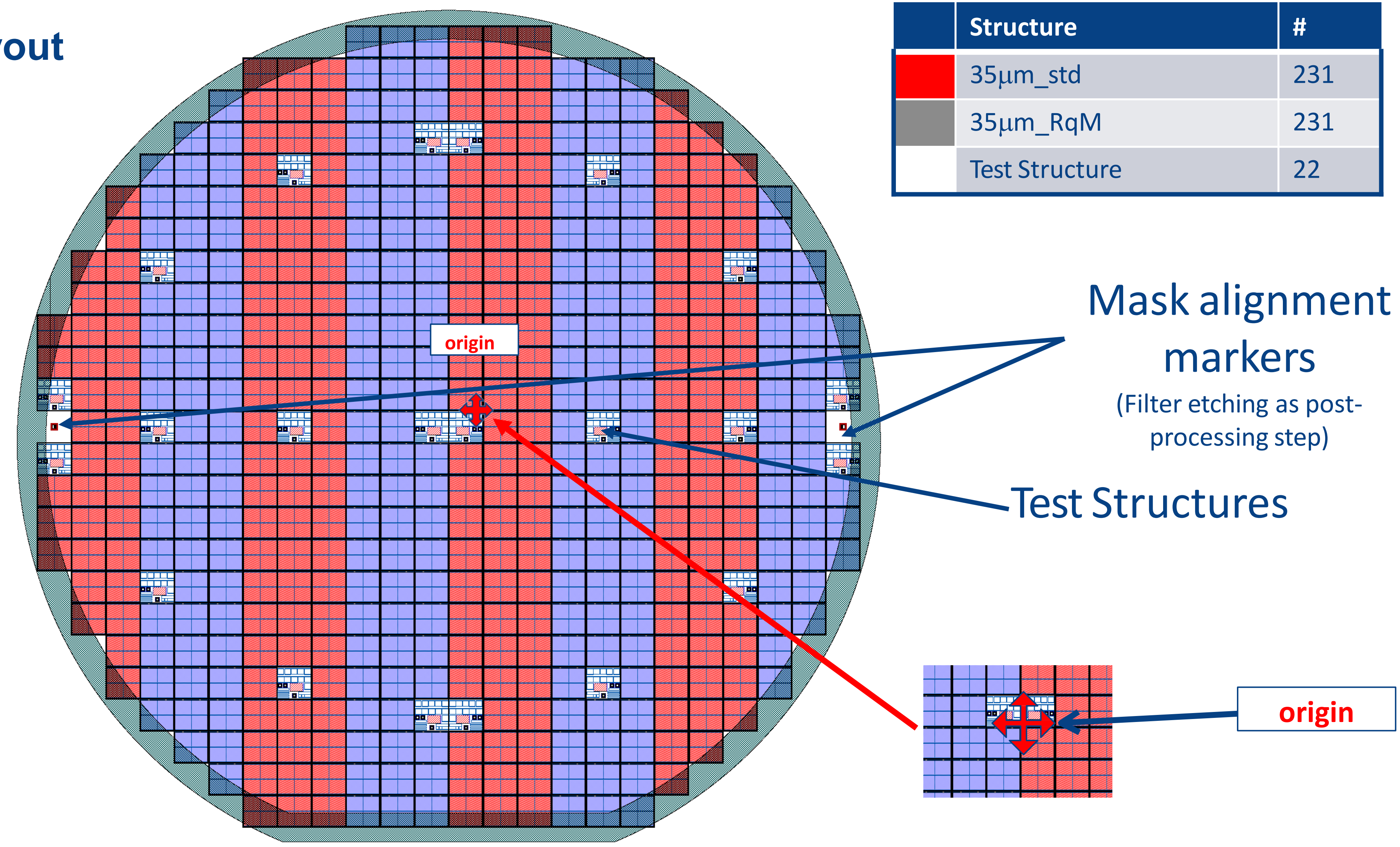




Configuration is suitable for readout of large calorimeter crystals, *e.g.,* Mu2e
2x3 array of 6x6mm devices with series/parallel biasing

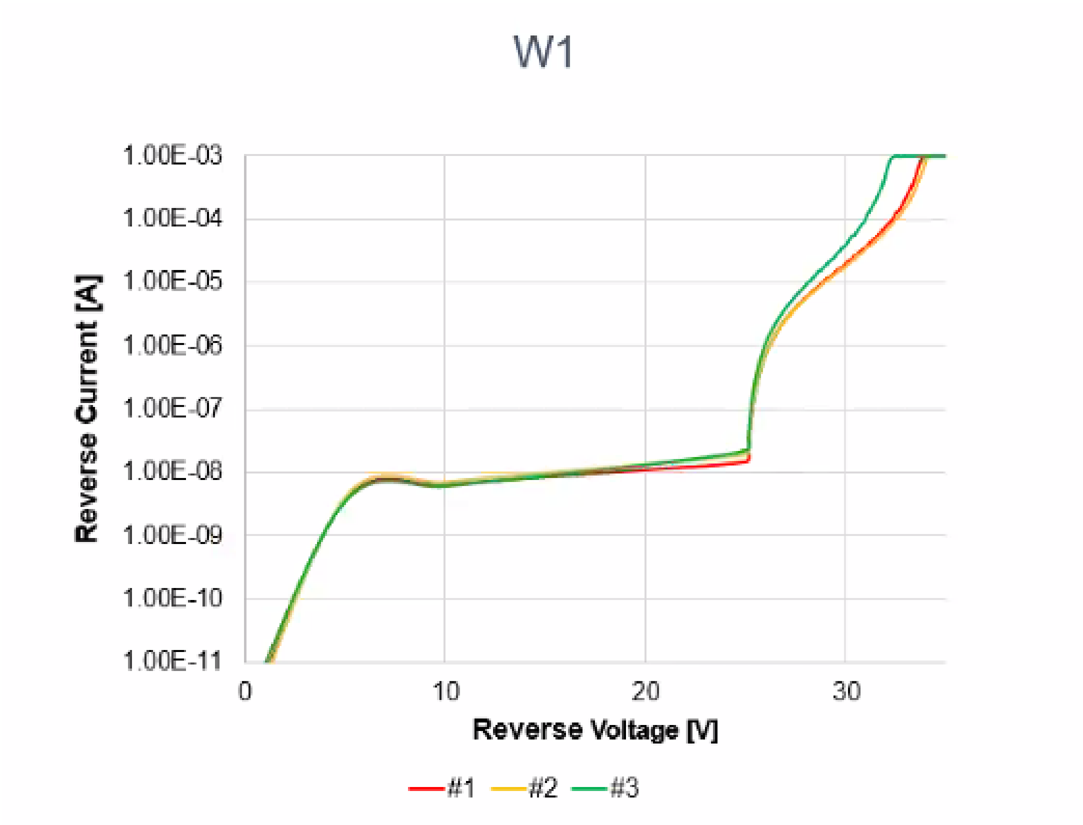
Wafer level production and processing

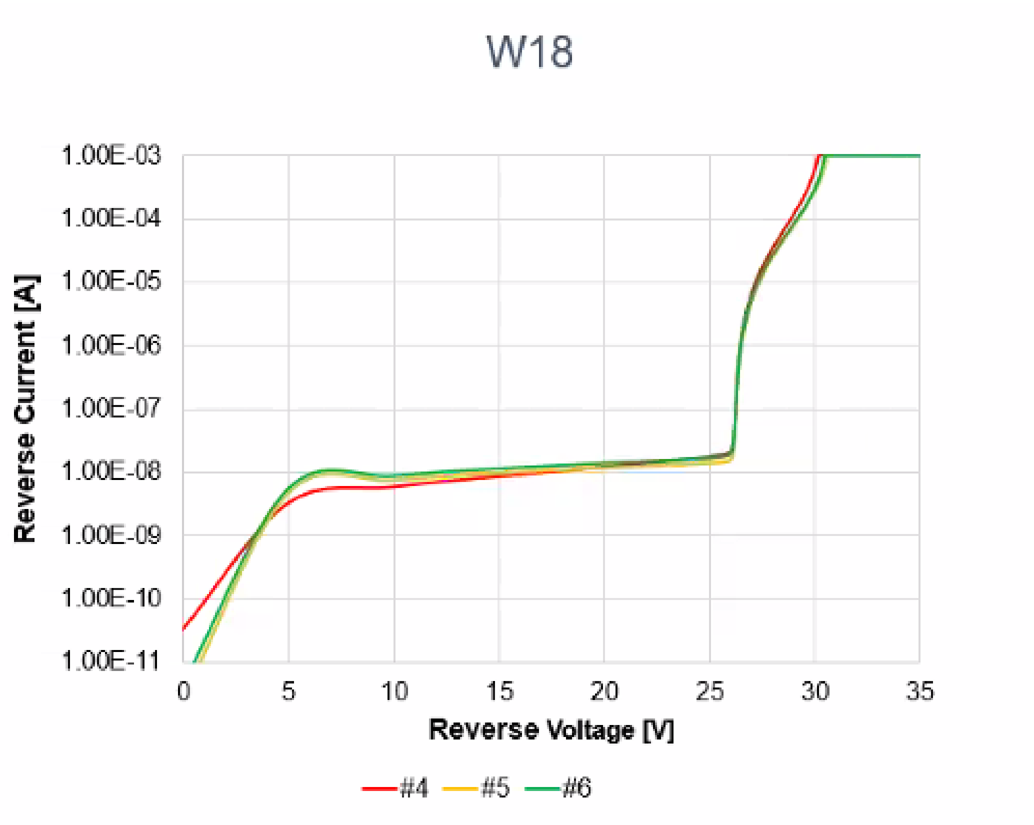
Wafer Layout



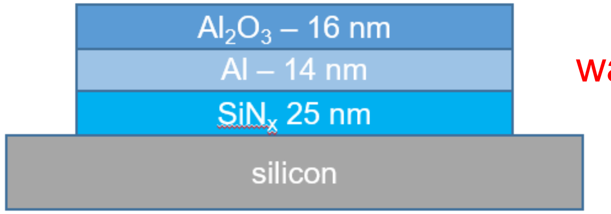
	Structure	#
	35μm_std	231
	35μm_RqM	231
	Test Structure	22

IV curves for new wafers

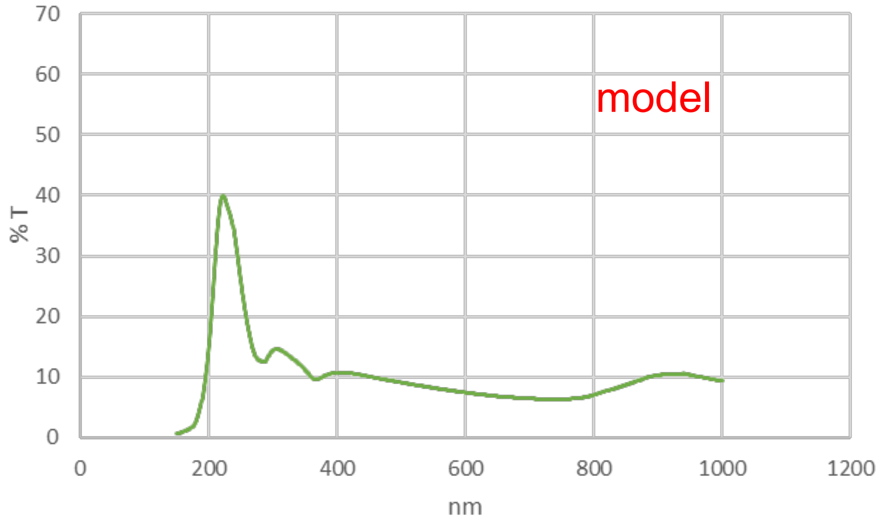


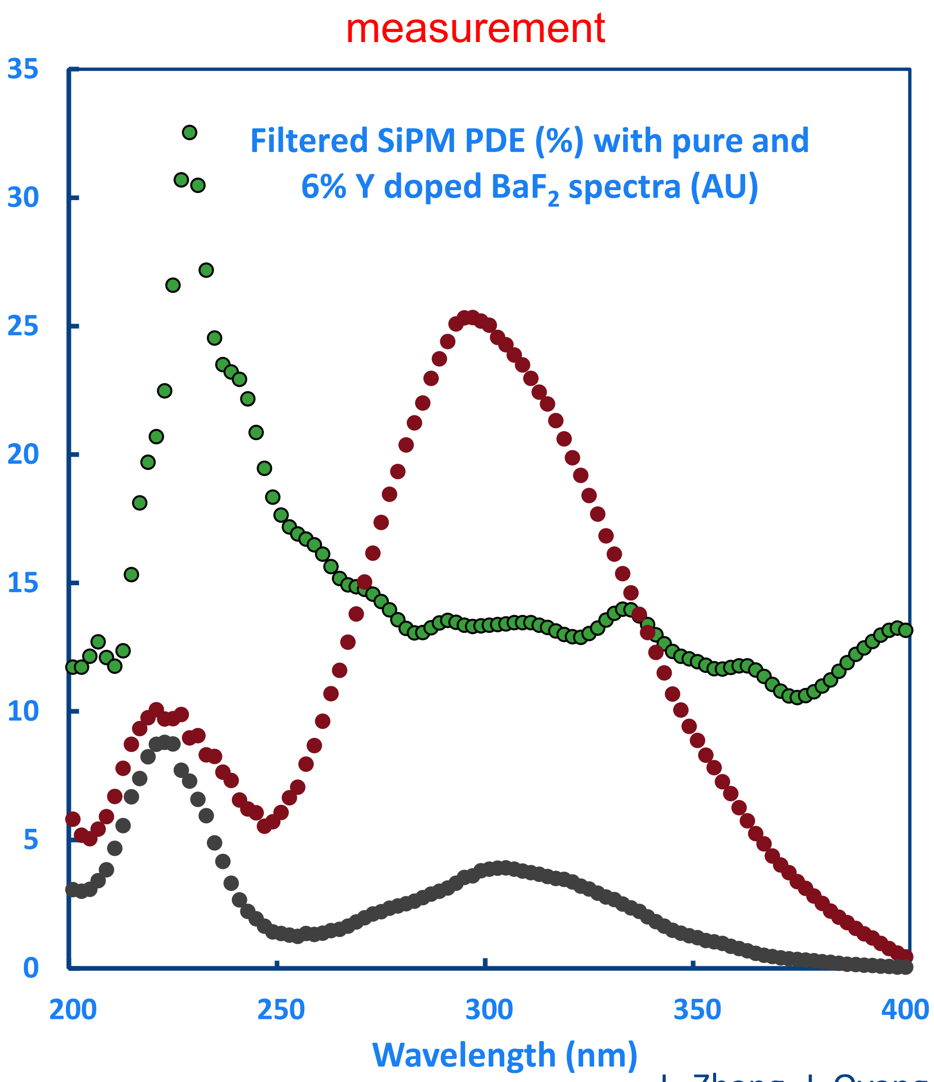


Integrated three-layer filter on an FBK SiPM



wafer 11





L. Zhang, J. Oyang

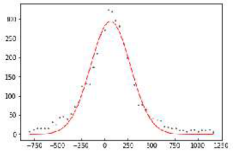
PDE scanned *vs.* wavelength at several bias voltages, with gain measured

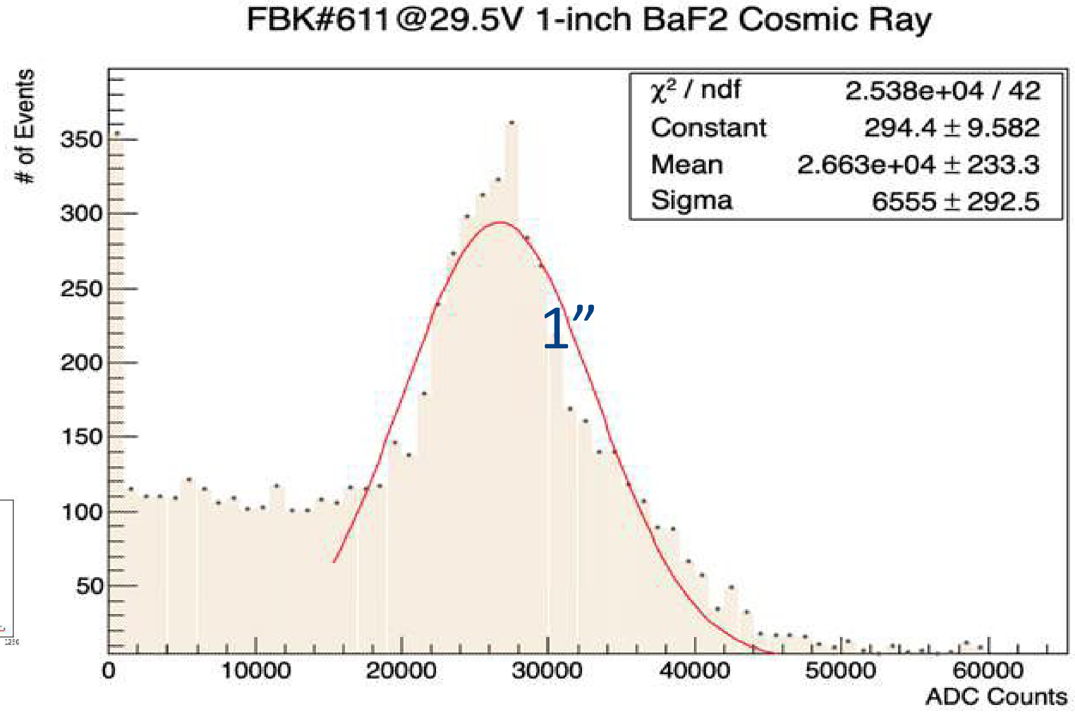
Calibrated with pulsed LED @ 465 nm for SiPM bias at 29 V

Excess noise factor determined at each bias

FBK #611 BaF_2 Cosmic Ray Spectrum

Pedestal

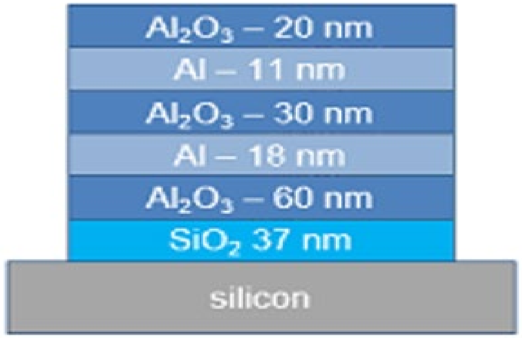


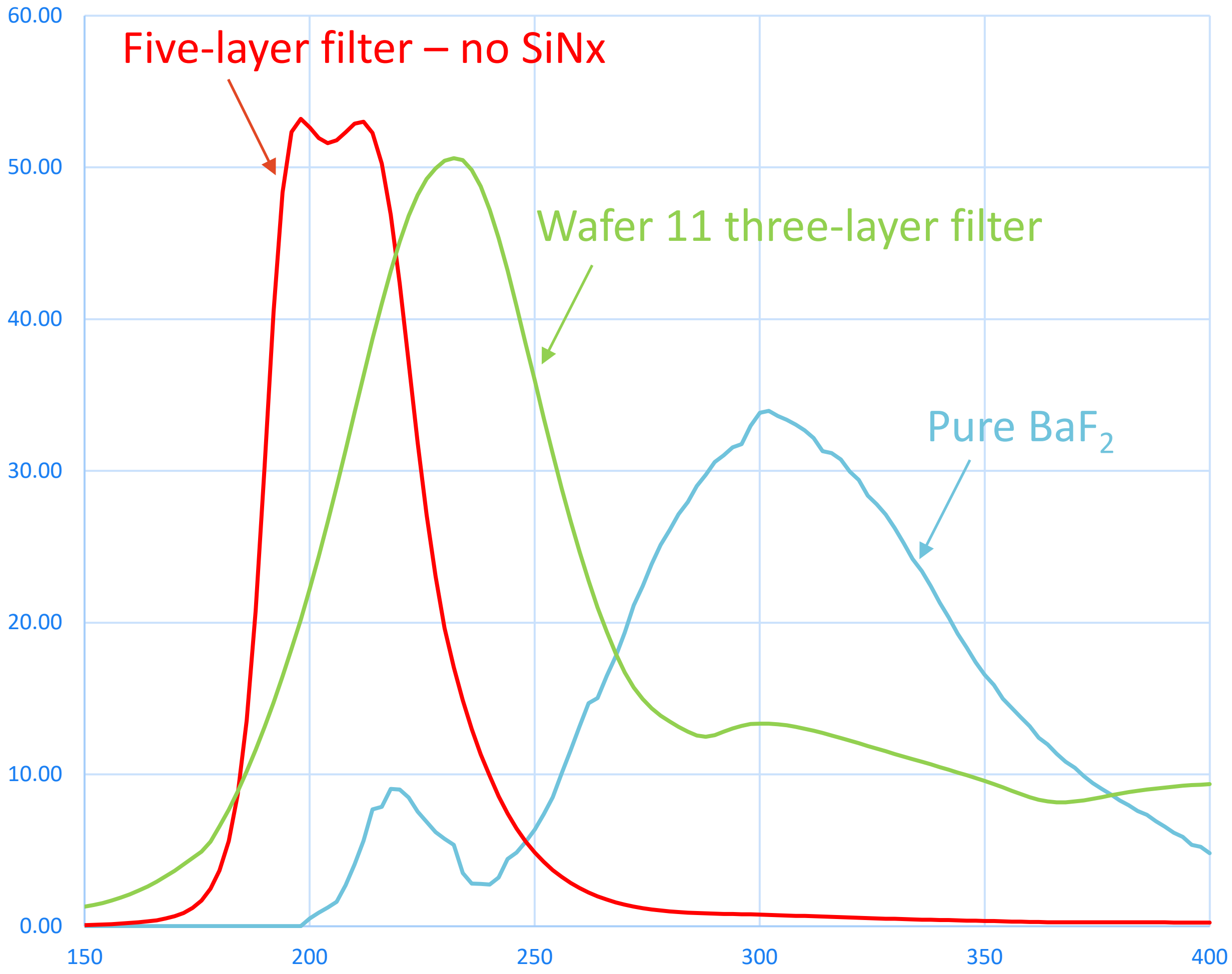


- FBK SiPM #611, dimension 6x6 mm, operated at 29.5V
- BaF_2 dimension 1" x 1" x 1", wrapped with teflon with an opening of 6x6 (mm)
- Cosmic ray deposits 6.374 MeV/cm * 2.54 cm = 16.2 MeV
- (26631 - 68) adc / 148 pe/adc = 180 pe
- 180 pe / 16.2 MeV = 11 pe/MeV   With 2x3 array, expect 60-70 pe/MeV

Five-layer filter design – calculation

- The bandpass of the five-layer filter (this design assumes complete removal of SiNx passivation) is narrower, encompasses the small 195nm fast component and has superior suppression of the slow component

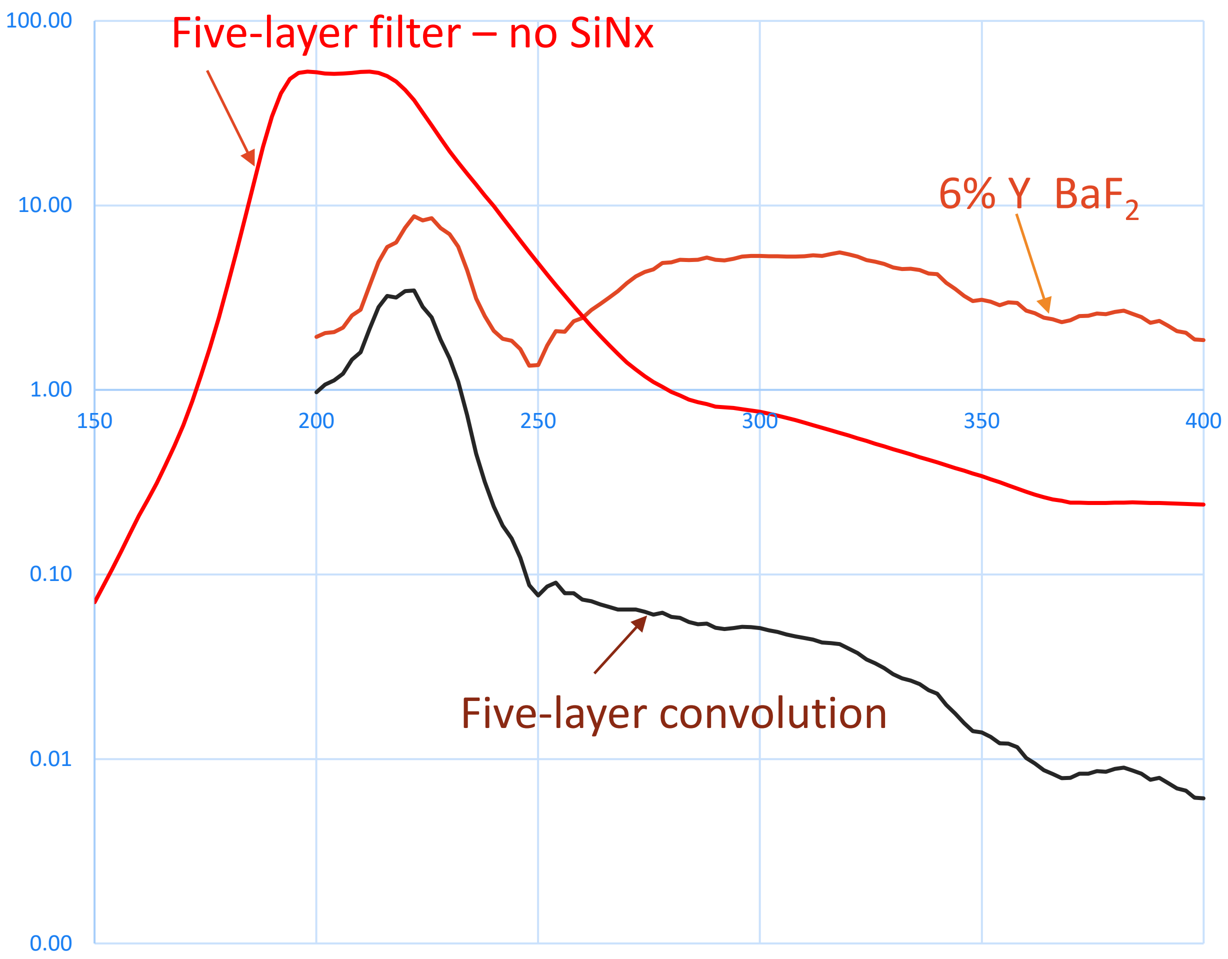




Fast/slow component readout performance

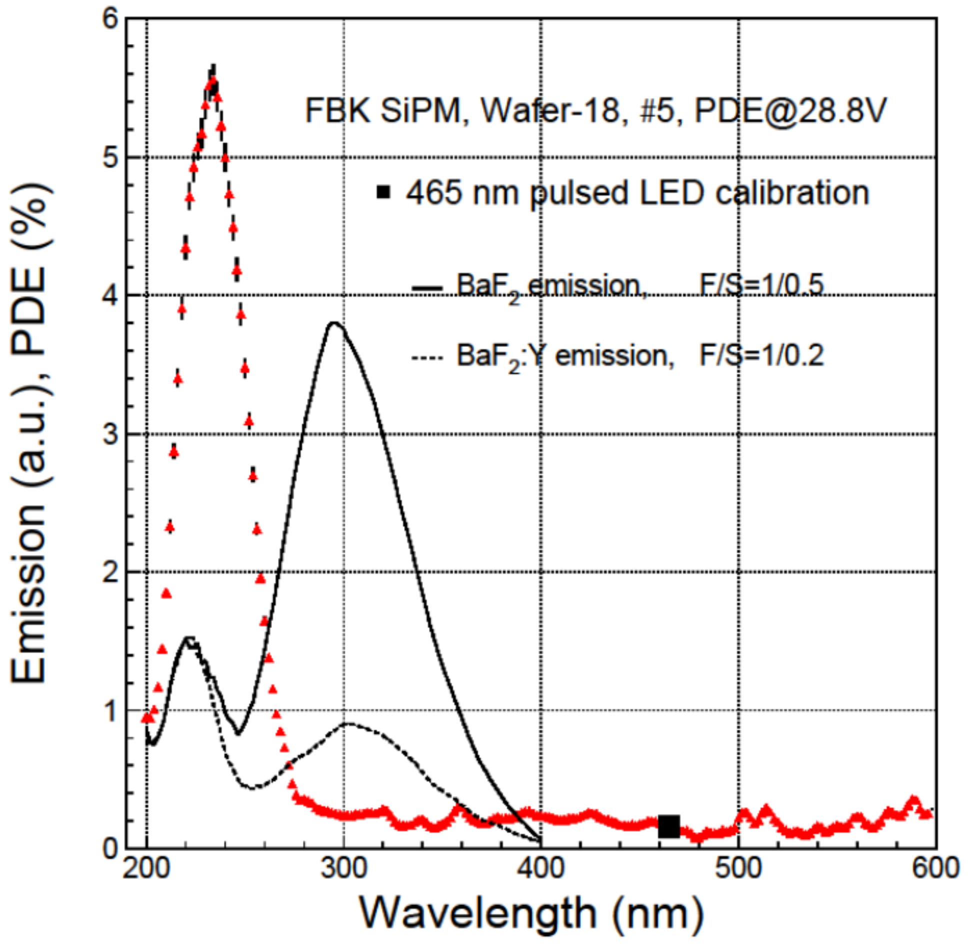
- Combining
  - 6% Y-doped BaF_2 and
  - SiPM with a five-layer filter

  provides further improvement in the ratio of fast-to-slow scintillation components
- This performance should work well for the Mu2e-II calorimeter and other high-rate applications

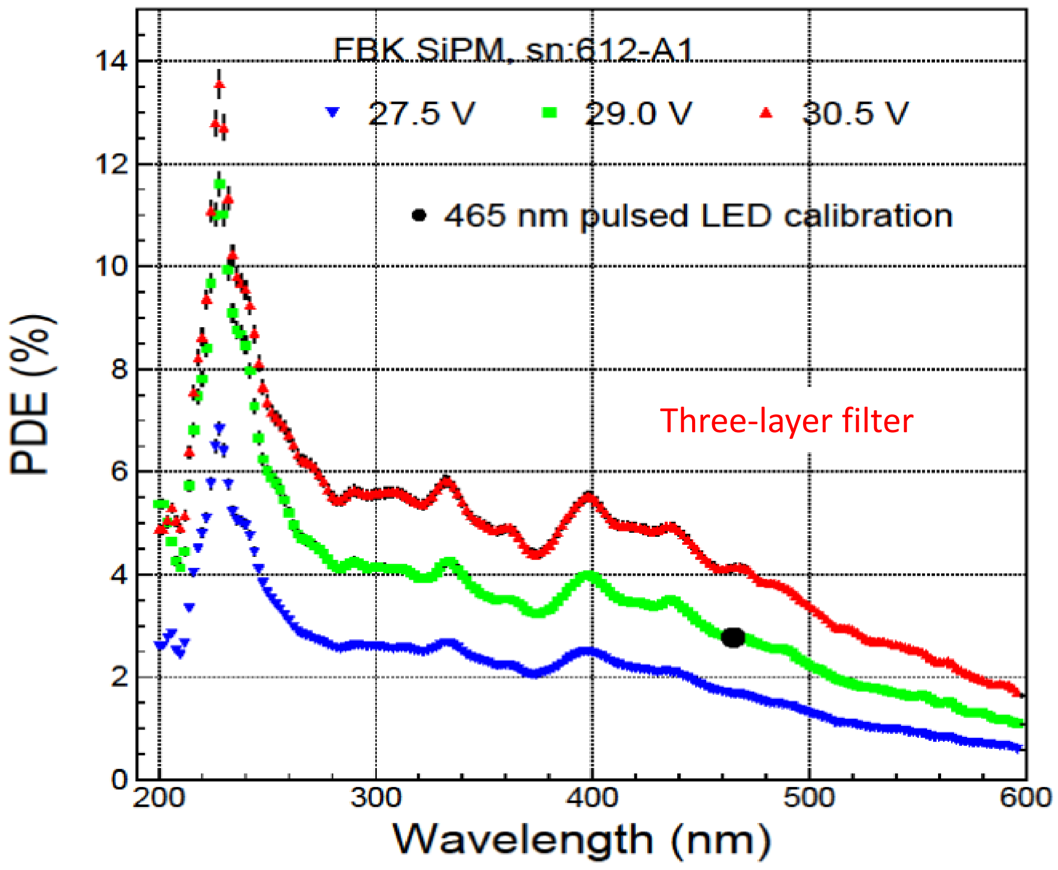


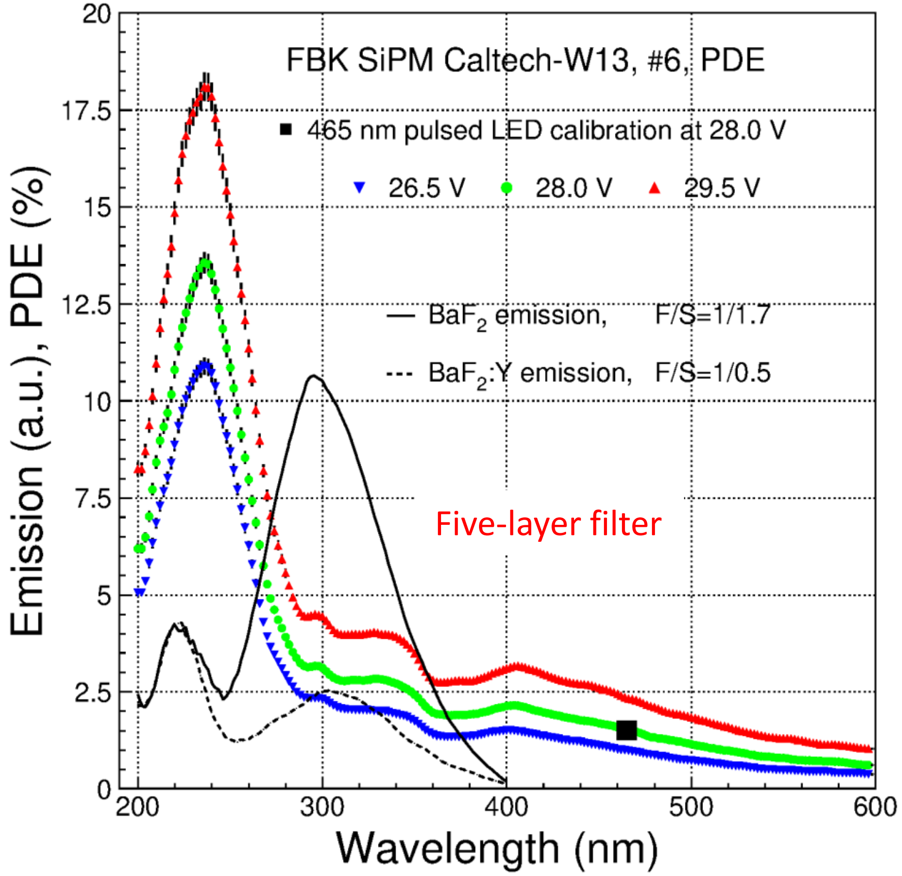
Integrated five-layer filter on an FBK SiPM – first attempt

- ❑ PDE of a five-layer filter SiPM
- ❑ The good news
  - ❑ Better centering on fast component
  - ❑ Better suppression of slow component
- ❑ The bad news
  - ❑ Higher leakage current ⇒ more noise
  - ❑ Lower PDE at peak
- ❑ Running at lower temperature can improve leakage current and PDE
- ❑ A new wafer with different initial passivation has been fabricated and JPL has applied a new five-layer filter
- ❑ We expect the same or better bandpass performance and higher PDE



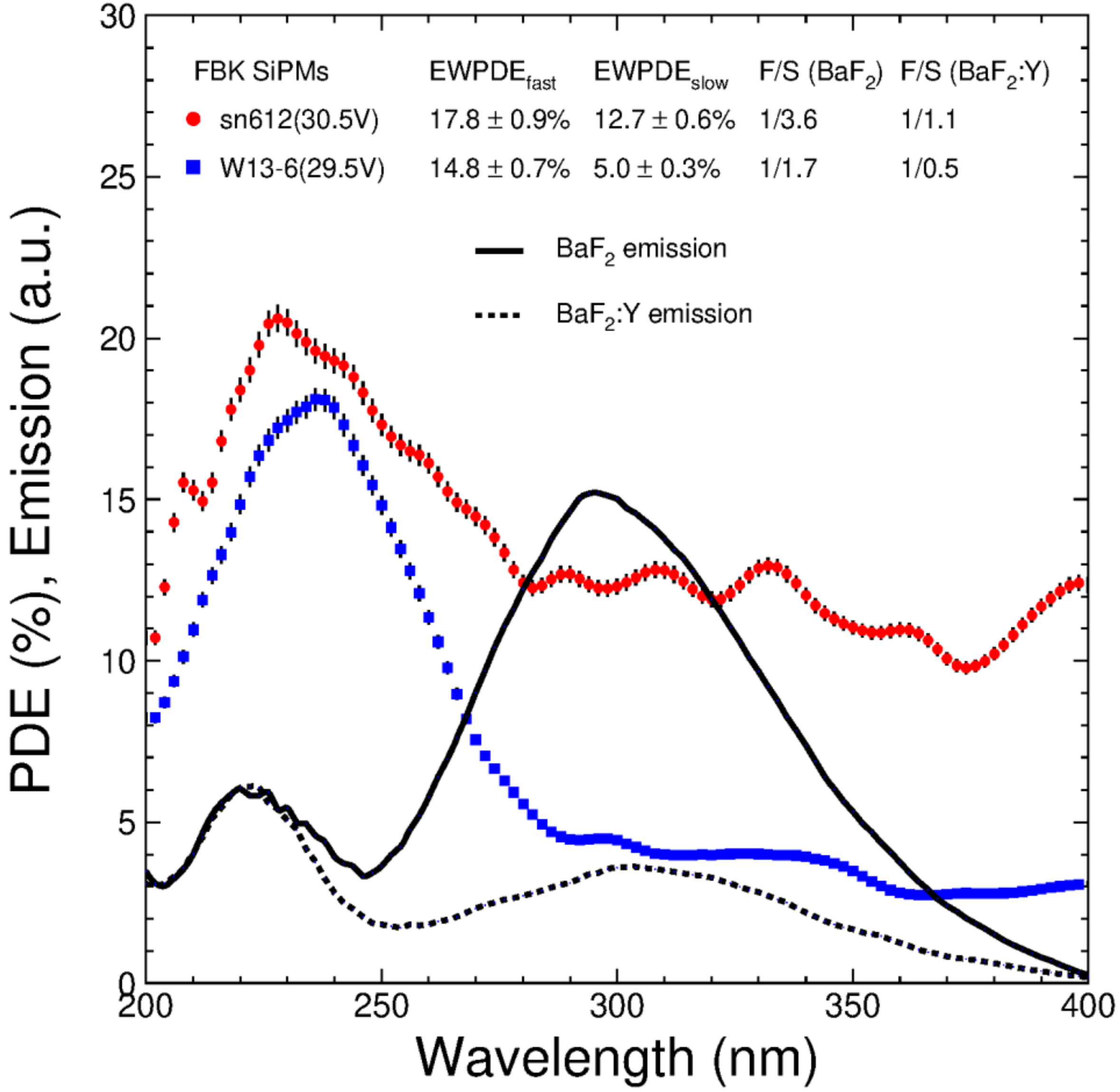
New five-layer filter





Success!

Three-layer/five-layer comparison



CIT/JPL/FBK SiPM - a phased approach

- Develop a SiPM with an integrated filter for readout of BaF_2 fast component
- Building on our experience with a large area APD developed with RMD, we have adopted a phased SiPM development approach

DONE
1. Build a **three-layer ALD filter** on a 6x6 mm NUV SiPM structure, exploring different SiNx passivation layers, guard ring structures, …
2. Fabricate **2x3 arrays of the 6x6 mm chips**, biased in series parallel configuration à la MEG and Mu2e to read out larger crystals

DONE
3. Improve slow component rejection with more sophisticated **five-layer filters**

4. Use **delta doping** and **backside illumination** to improve PDE, effectiveness of the filter, timing performance and UV tolerance

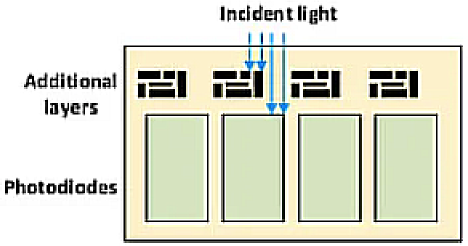
DONE
- Explore diode structures of various sizes to pinpoint source of leakage current

Underway
- Explore MBE recipes for producing delta-doped layers

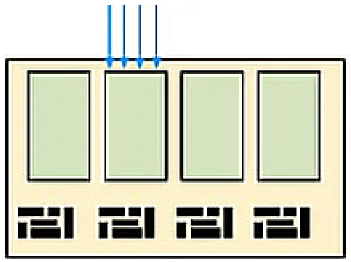
Not funded
- Fabricate back-illuminated SiPMs with a five-layer filter and delta-doping

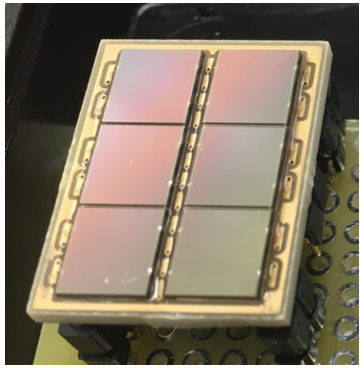
Configuration is suitable for readout of large calorimeter crystals, *e.g.,* Mu2e
2x3 array of 6x6mm devices with series/parallel biasing

Front illuminated



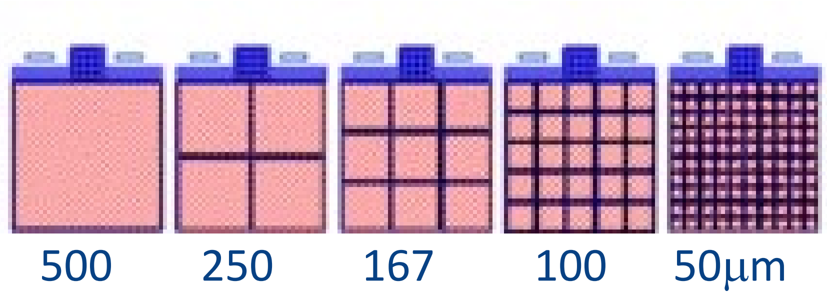
Back illuminated

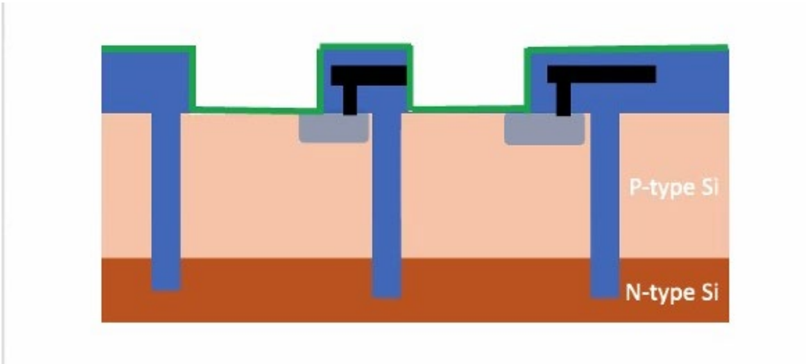




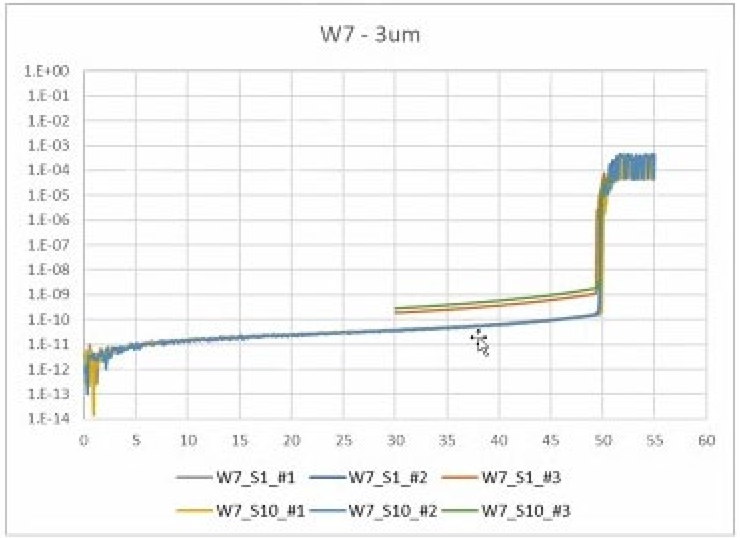
Next steps

1. **Understand the origin of leakage current before MBE growth: is it surface or trenches?**
   a. In order to decouple the details of fabricating surface structures from the avalanche structures, we made photodiode (*i.e.,* no gain) structures with differing numbers of cells in a given area and different surface treatment





Caltech Diodes
IV Measurements



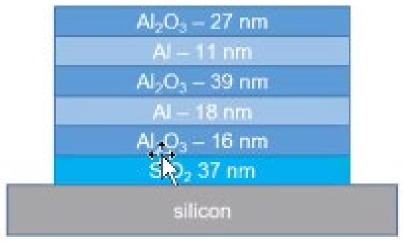
Vbd ~50V

Next steps

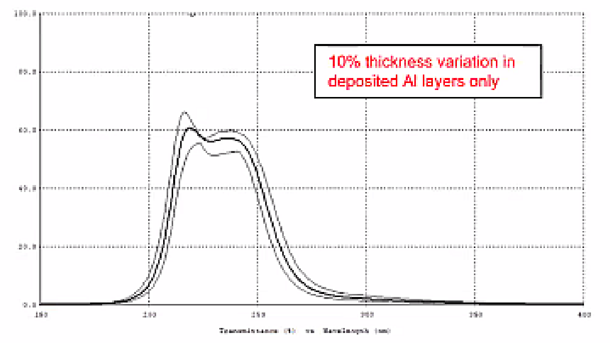
2. Optimization of the MBE superlattice layer parameters

a. Add a several different variants of superlattice to the diode structures to optimize leakage current, waveform performance. PDE

3. Incorporate more complex filters



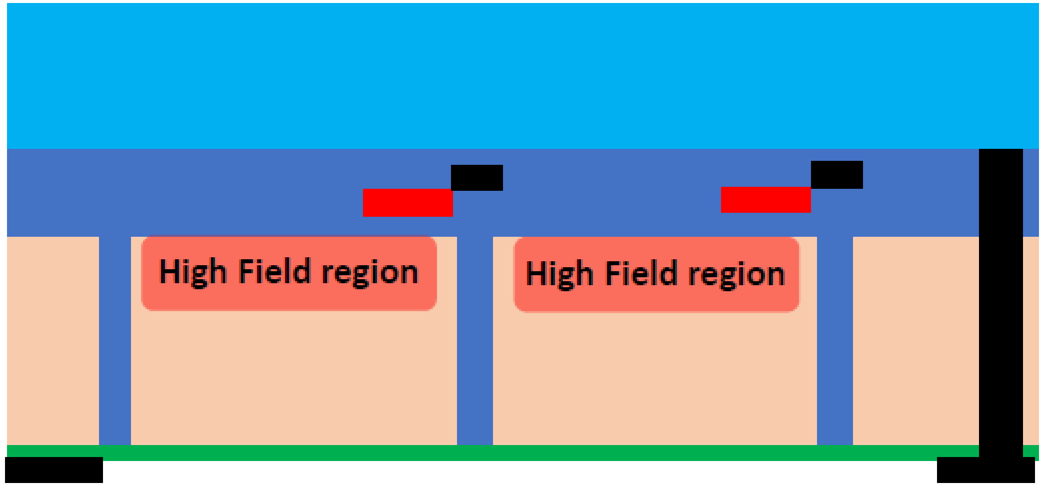
Process variation study



Next steps – the ultimate goal

4. Produce a backside illuminated SiPM with an optimized superlattice and a five layer filter

- ❑ Decouples the illumination/collection region and the high field avalanche region
- ❑ Provides a higher fill factor
- ❑ Provides robust protection against damage from UV scintillation light
- ❑ Allows for more options for the filter design
- ❑ Requires wafer thinning and bonding



- ❑ Design will incorporate what we learn from MBE on the photodiode structures
- ❑ **Awaits funding**

Conclusions

- Barium fluoride, which has the fastest decay time scintillation light of any known inorganic crystal, is an attractive candidate for high energy physics and PET scanning, provided that an appropriate sensor can be developed
- We have made a successful internally filtered SiPM
  - We have shown that a high QE internal filter with strong suppression of the slow scintillation component can be fabricated
  - We are currently optimizing the parameters of the MBE layer, using diode structures
  - We will then be ready to produce the large-area back-illuminated SiPM needed for a substantial BaF_2 readout application

Barium fluoride scintillation spectrum

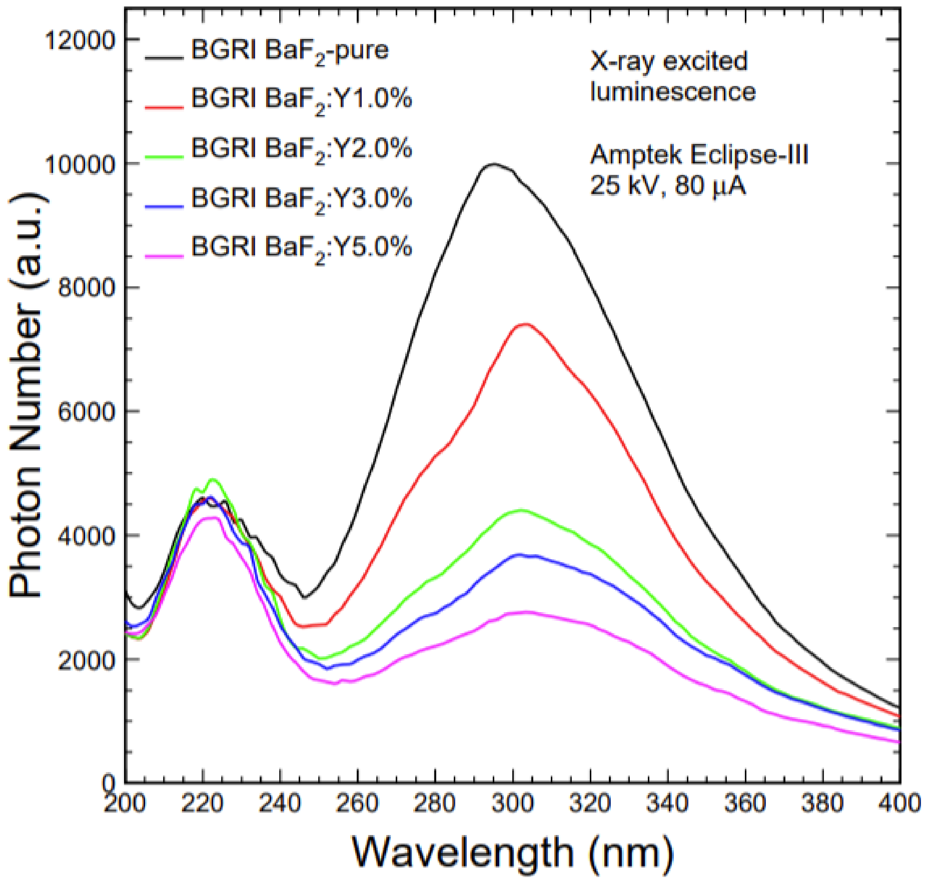


FIG. 20. X-ray excited emission spectra measured for BGRI BaF_2 crystal samples with different yttrium doping level.

Barium fluoride – PMT vs MCP

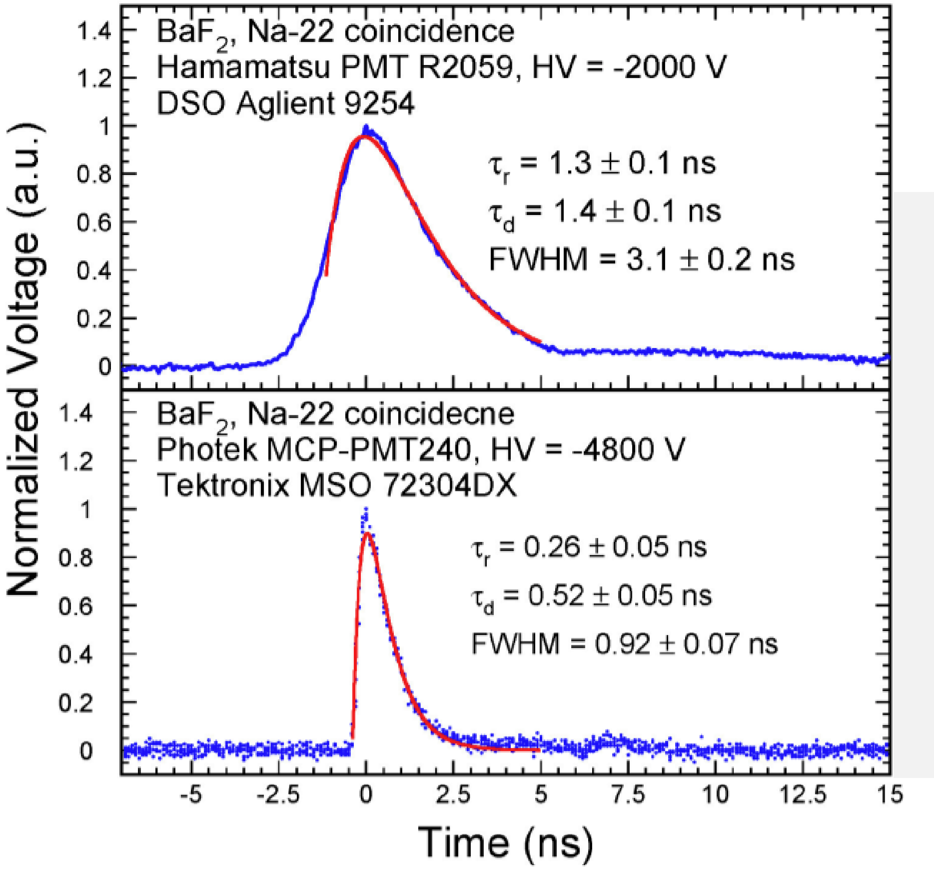


FIG. 19. A comparison of BaF_2 pulse shape measured with a Hamamatsu R2059 PMT (top) and a Photek MCP-PMT 240 (bottom).

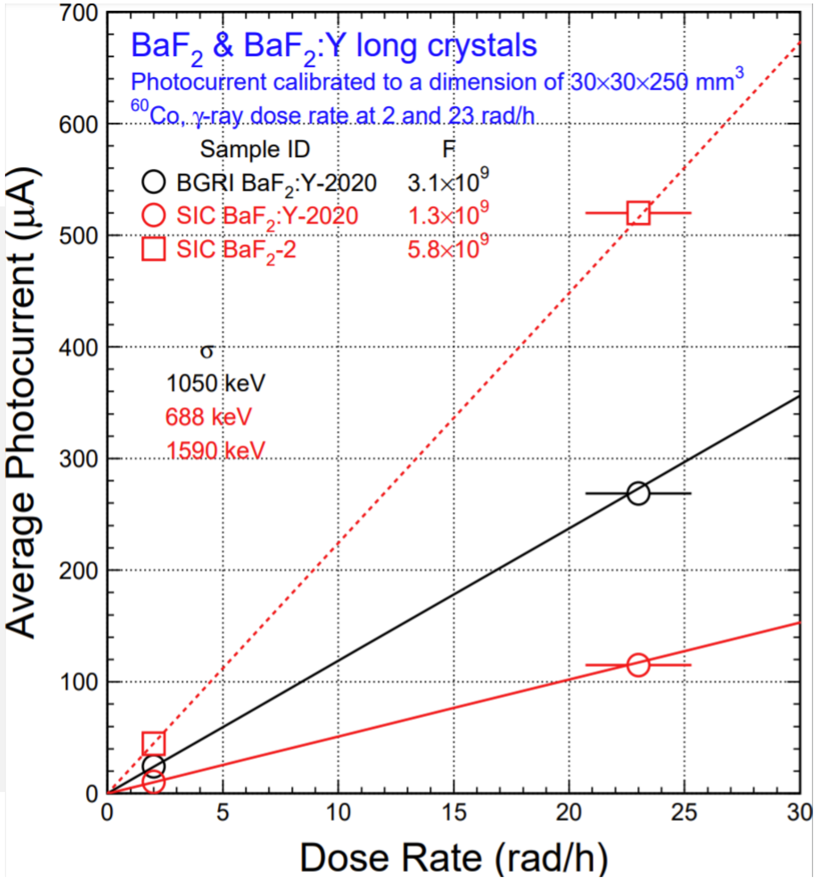


FIG. 21. Photocurrent is shown as a function of the dose rate for an SIC BaF_2 and two BGRI and SIC BaF_2:Y samples of calorimeter size under ionization dose rate of 2 and 23 rad/h.

Zhu

Integrated three-layer filter on an FBK SiPM

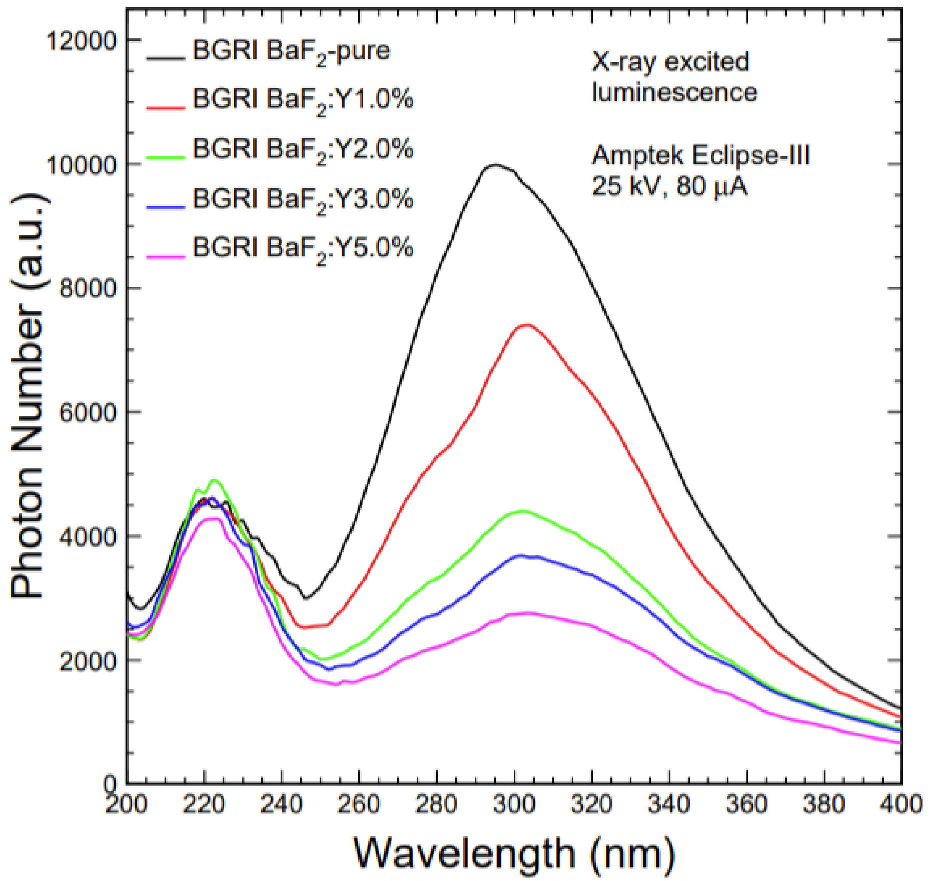


FIG. 20. X-ray excited emission spectra measured for BGRI BaF_2 crystal samples with different yttrium doping level.

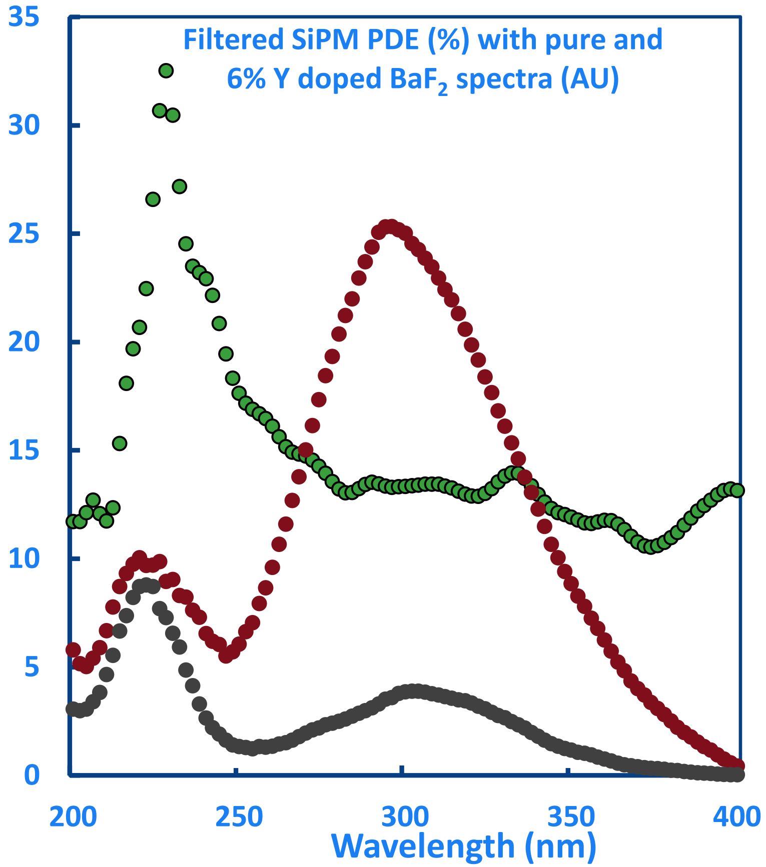
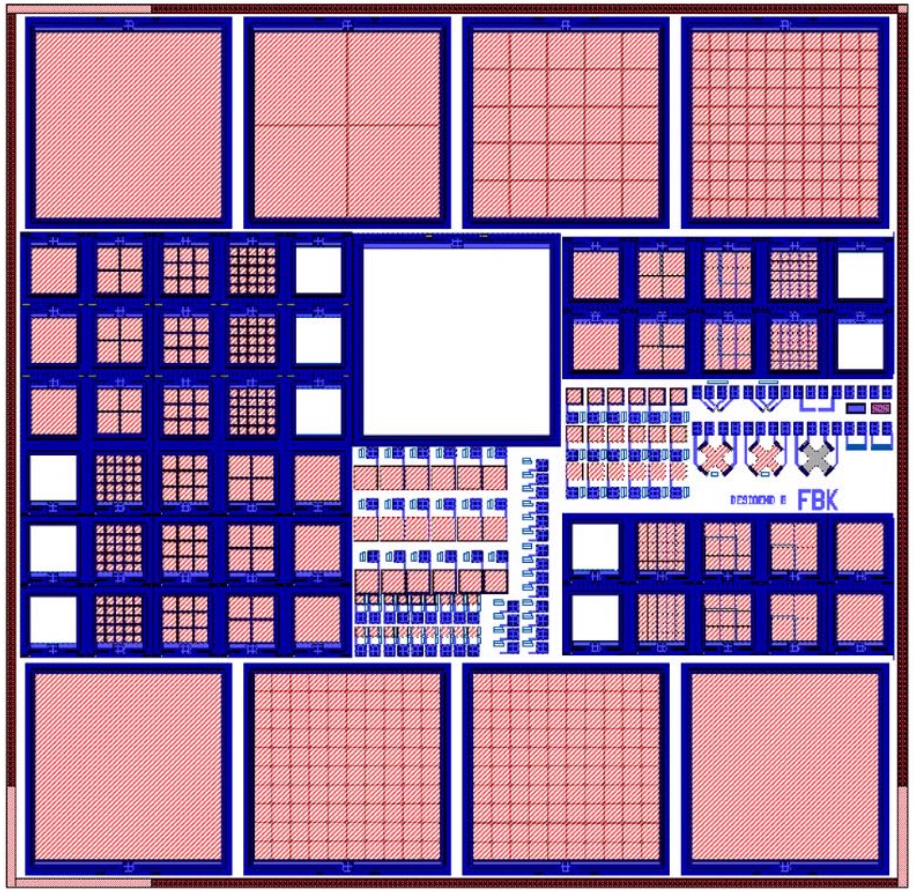


FIG. 22. Scintillation spectrum of pure BaF_2 and BaF_2 doped with 6% Y, compared with the measured PDE of a 6 × 6mm SiPM with an integrated filter.

Photodiode wafer layout

Shot composition

Splits	Layout	AA/SIR Overlap	Trench/ SIR
1	L1	Overlap1	no Dist
2	L1	Overlap2	no Dist
3	L1	Overlap1	Dist1
4	L1	Overlap2	Dist1
3	L1	Overlap1	Dist2
4	L1	Overlap2	Dist2
5	L2	Overlap1	no Dist
6	L2	Overlap2	no Dist
7	L2	Overlap1	Dist1
8	L2	Overlap2	Dist1
7	L2	Overlap1	Dist2
8	L2	Overlap2	Dist2
9	L3	Overlap1	no Dist
10	L3	Overlap2	no Dist
11	L3	Overlap1	Dist1
12	L3	Overlap2	Dist1
11	L3	Overlap1	Dist2
12	L3	Overlap2	Dist2



Shot size ~10x10mm^2

2

A next generation crystal EMC

- To cope with higher radiation levels and higher rates in a magnetic field in an experiment such as Mu2e II, we would like to
  - Use Y-doped barium fluoride crystals
  - Have a photosensor that is sensitive only to the fast scintillation component
  - Improve the quantum efficiency
  - Extend the lifetime of the sensor under the intense UV scintillation light
- Our solution is a large area, back-illuminated UV-extended SiPM array with an integrated bandpass filter applied by atomic layer deposition, incorporating a quantum well structure produced by molecular beam epitaxy
- We have formed a collaboration of the Bruno Kessler Foundation (FBK), the Microdevices section of the Jet Propulsion Lab (JPL) and Caltech to develop such a device