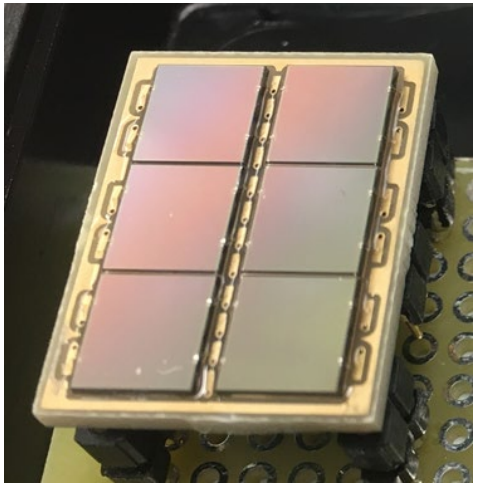
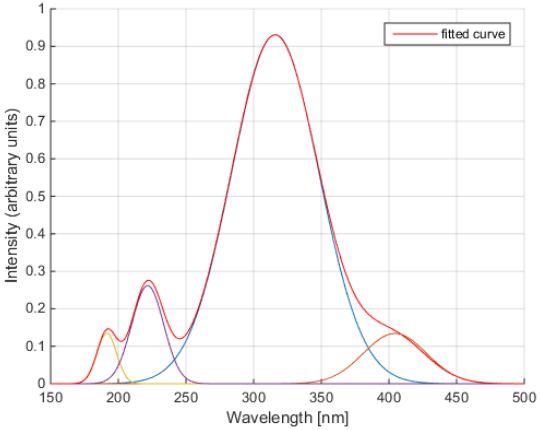
Progress on a photosensor for the readout of the fast scintillation light component of BaF_2



David Hitlin
Caltech
CPAD Instrumentation Frontier Workshop
March 18, 2021

BaF_2 scintillator and photosensors



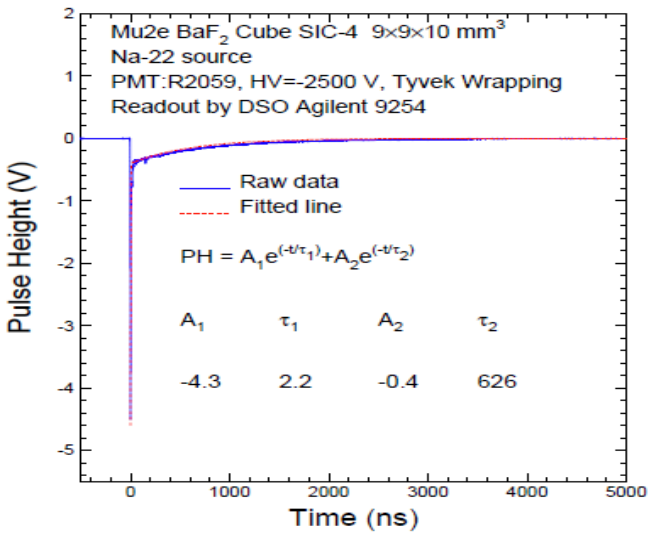
- BaF_2 is an excellent candidate for a fast, high rate, radiation-hard crystal for the Mu2e-II calorimeter, provided that one has a way of utilizing the **220 nm** cross-luminescence fast component (1500 photons/MeV) without undue interference from the larger **320 nm** slow component
  - There are actually two fast components (τ = 0.6 ns) at 195 and 220 nm and two slow components (τ = 630 ns) at 320 and 400 nm
- Our approach to BaF_2 calorimetry
  1. Suppress the BaF_2 slow component by Y doping, as developed by Zhu *et al.*,: a major advance, although much R&D remains to be done
  2. Develop a photosensor that is sensitive only to the fast component, is rad-hard and works in a magnetic field – our solution is a large area SiPM

The photosensor is being developed by a Caltech/JPL/FBK collaboration:

Caltech	B. Echenard, D. Hitlin, J. Oyang, J. Trevor, L. Zhang, R-Y. Zhu
JPL	J. Hennessy, M. Hoenk, A. Jewell
FBK	A. Ficorella, A. Gola, G. Paternoster

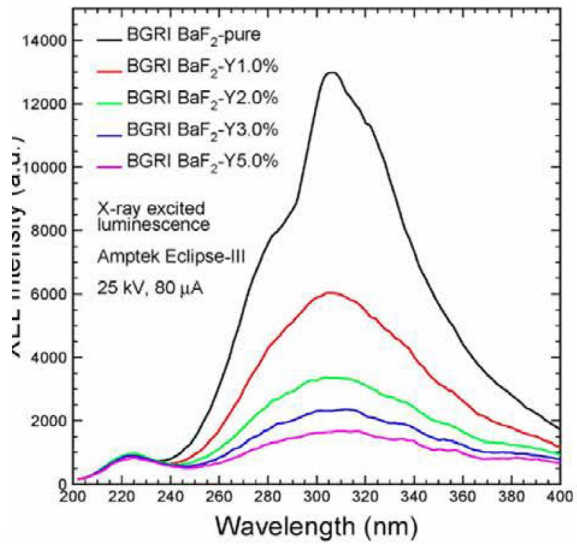
Pure and Y-doped BaF_2

Fast (220nm) and slow (320 nm) scintillation components

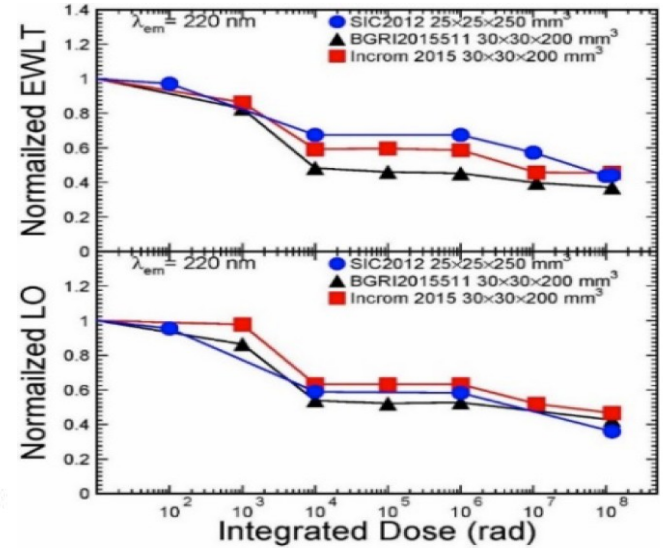


R.-Y. Zhu. *et al.*

Y doping can suppress slow scintillation component

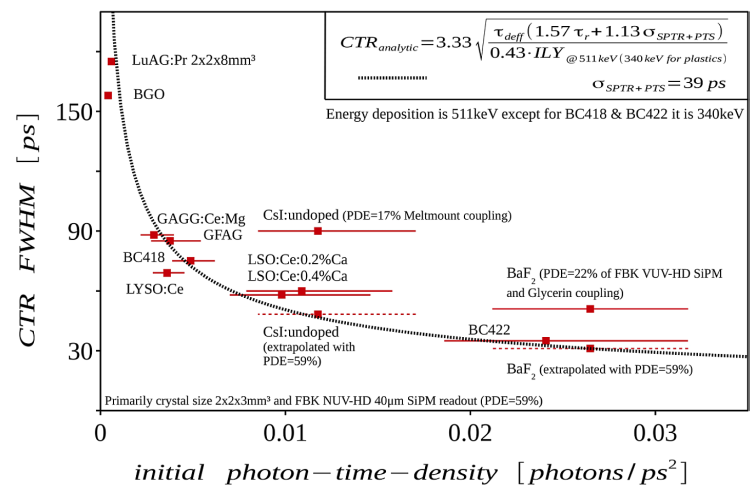


Radiation hardness (pure BaF_2)



BaF_2 with a VUV SiPM readout has the best experimental coincidence time resolution (CTR) achieved with PET-sized crystals

S. Gundacker, et al. ,
Phys. Med. Biol. **65,** 025001 (2020)



CIT/JPL/FBK SiPM - a phased approach

- Building on our experience with a large area APD developed with RMD, we have adopted a phased SiPM development approach

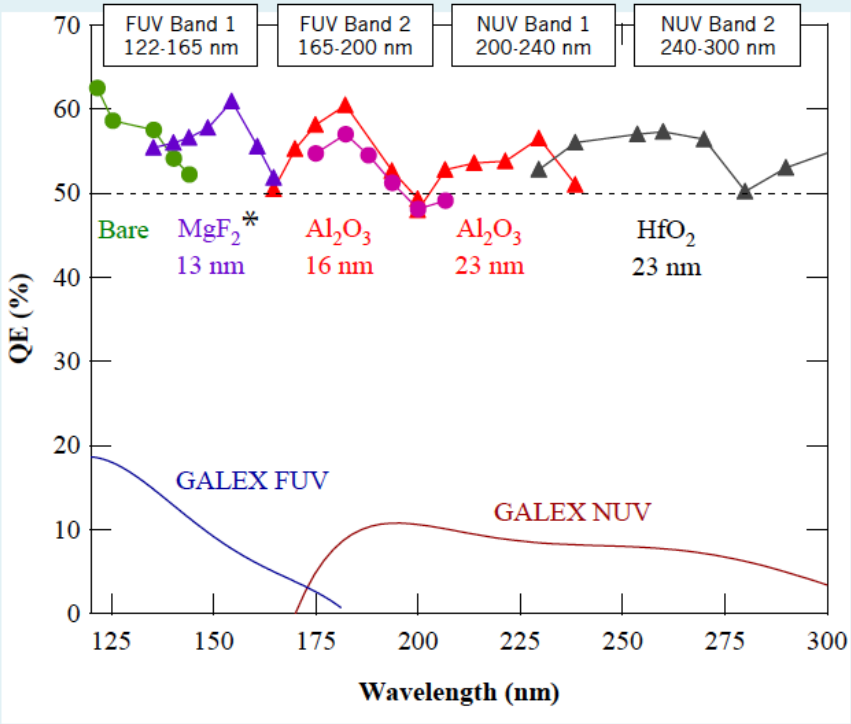
DONE

1. Incorporate 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
3. Improve slow component rejection with more sophisticated filters
4. Use delta doping and backside illumination to improve PDE, the effectiveness of the filter, and timing performance

- I will show results from the first 6x6mm chip arrays
  - I/V curves
  - Excess noise measurements
  - PDE as a function of wavelength, demonstrating filter performance
  - Radioactive decay and cosmic ray spectra with small BaF_2 crystals
- We have detailed plans for the next rounds of R&D, which will provide an improved filter, better UV tolerance and improved time response

ALD antireflection filters improve QE

AR Coatings for UV Detectors



*MgF_2 result for thermally evaporated film

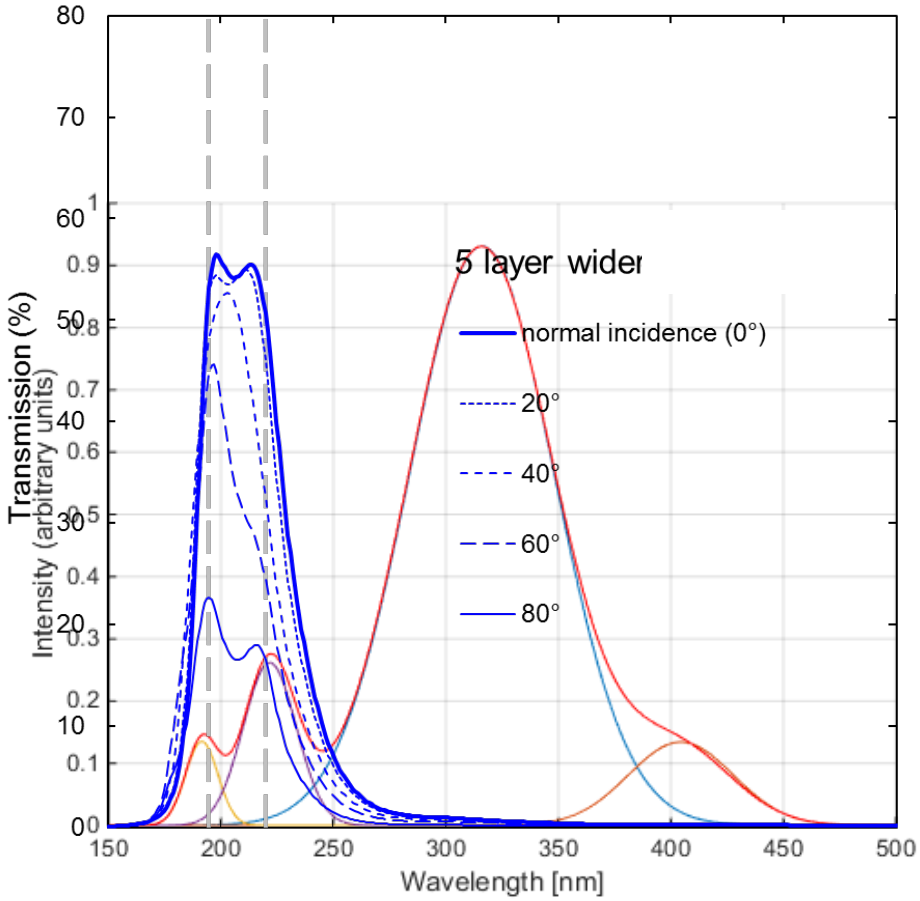
ALD-AR coatings provide up to **2X improvement** over uncoated baseline and a **5x-50x improvement** over incumbent UV detector technology

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

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

ALD bandpass interference filters

- A five-layer filter encompasses both the 195 nm and 220 nm peaks and provides improved slow component suppression
- Upper side performance has been measured on an APD at zero bias



Transmission of an interference filter is dependent on angle of incidence

The passivation layer on which the filter is constructed is SiO_2

ALD bandpass interference filters

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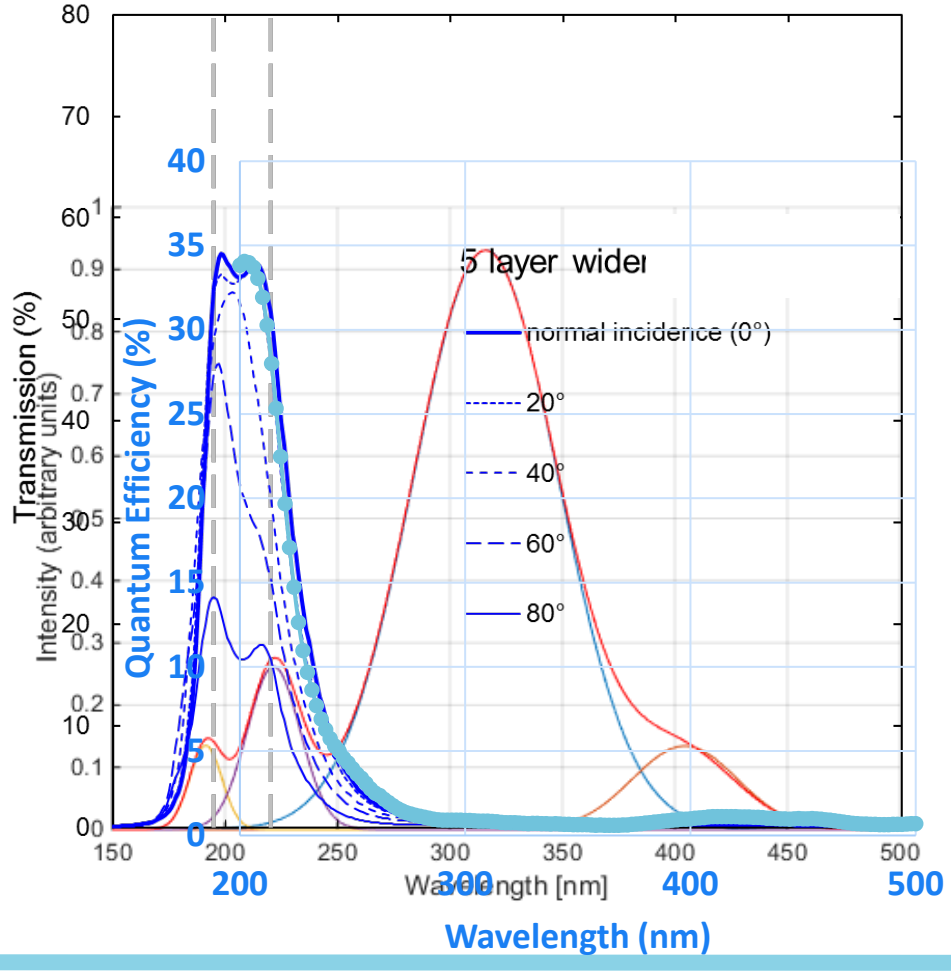
- Upper side performance has been measured on an APD at zero bias

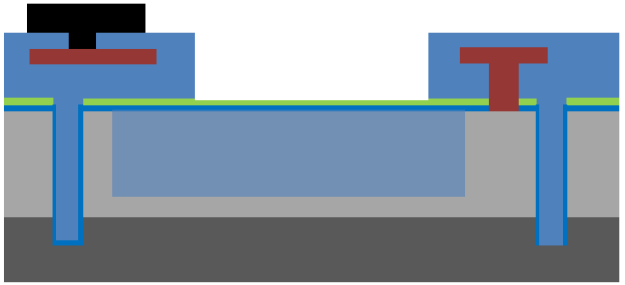


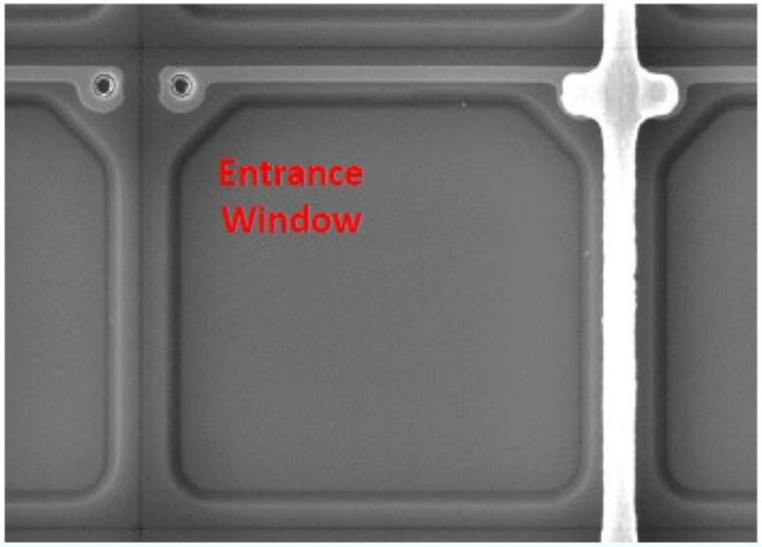
Measurement is scaled using a model to obtain the QE at nominal gain/bias

Fabricated RMD APDs worked well, but were fragile and noisy at room temperature

SiPM fabrication and test

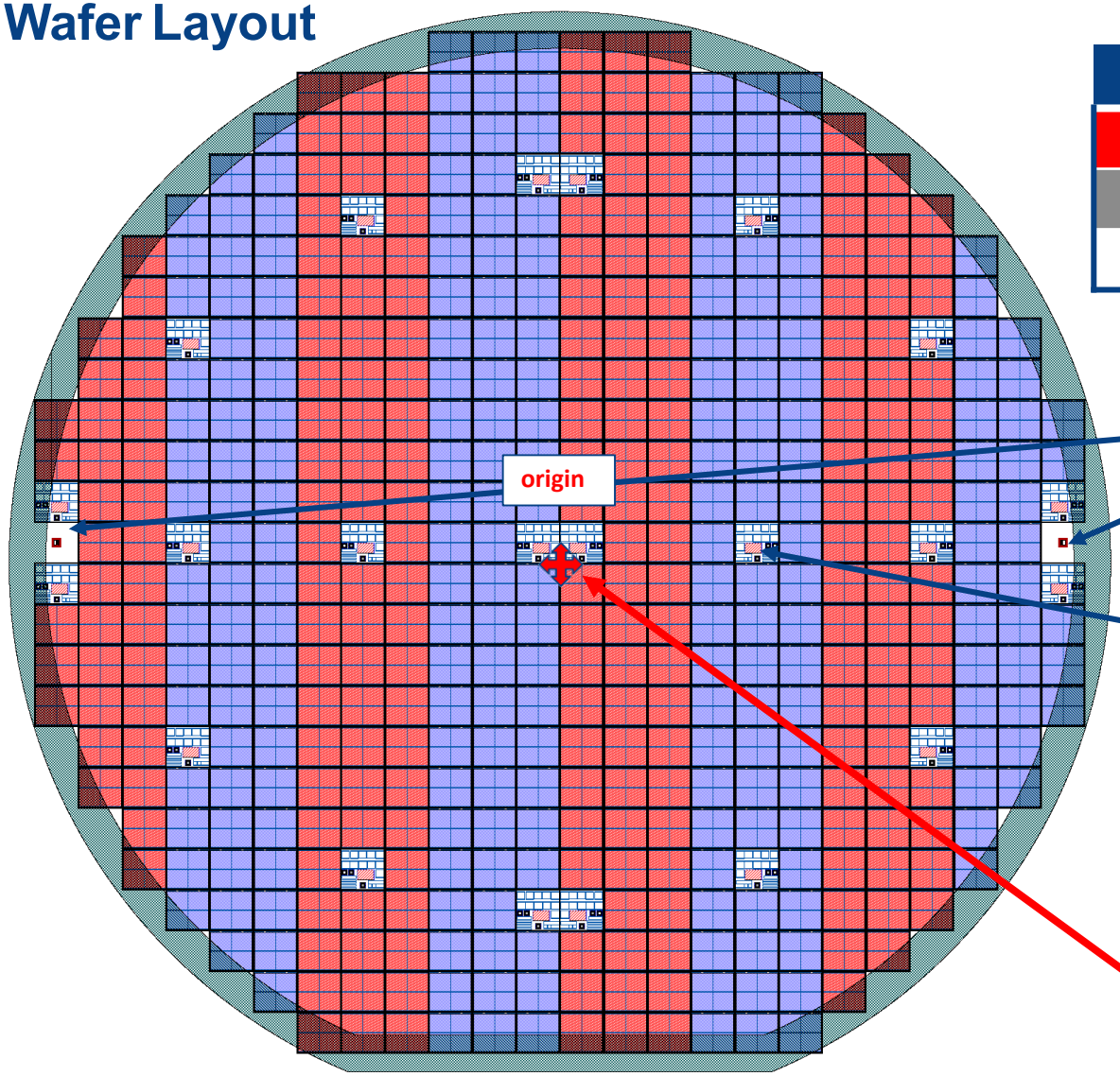
- FBK has fabricated wafers based on current NUV designs, with various modifications, including guard ring structures
- FBK thins or removes SINx passivation layer
- ALD filters are deposited at JPL
- The wafers are returned to FBK for probing and dicing into chips
- 6x6mm devices with three-layer filters have been fabricated and tested at Caltech
  - Filter performance and PDE as a function of wavelength have been measured with a spectrophotometer down to 200nm
  - We have characterized excess noise performance
  - We have then taken radioactive decay and cosmic ray spectra with pure BaF_2 crystals, measuring the fast/slow scintillation yield





Wafer level production and processing

Wafer Layout

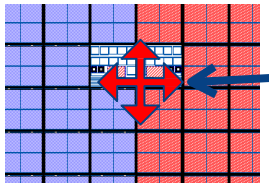


	Structure	#
	35µm_std	231
	35µm_RqM	231
	Test Structure	22

Mask alignment markers

(Filter etching as post-processing step)

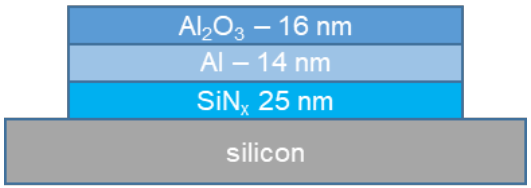
Test Structures



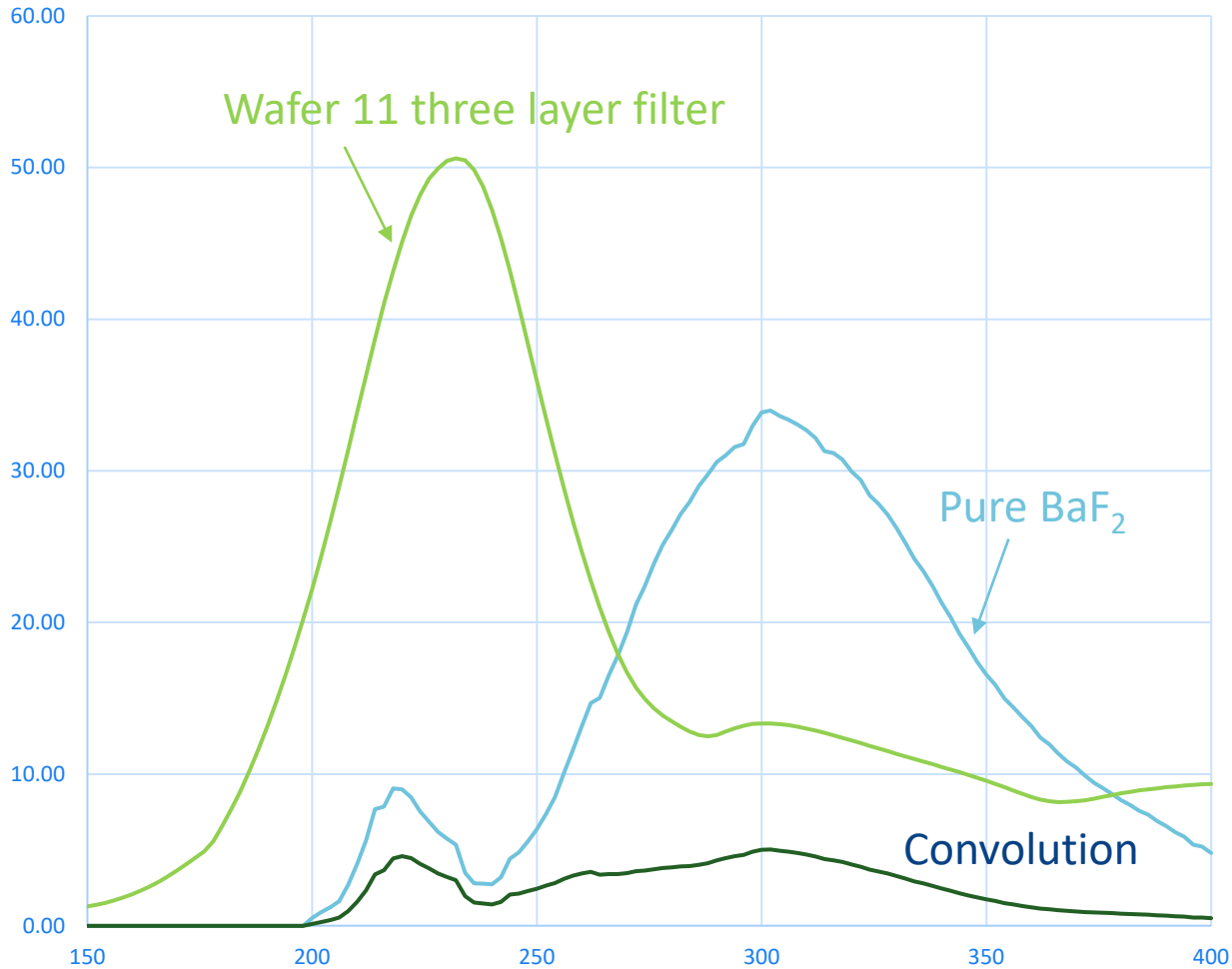
origin

Initial three-layer SiPM filter

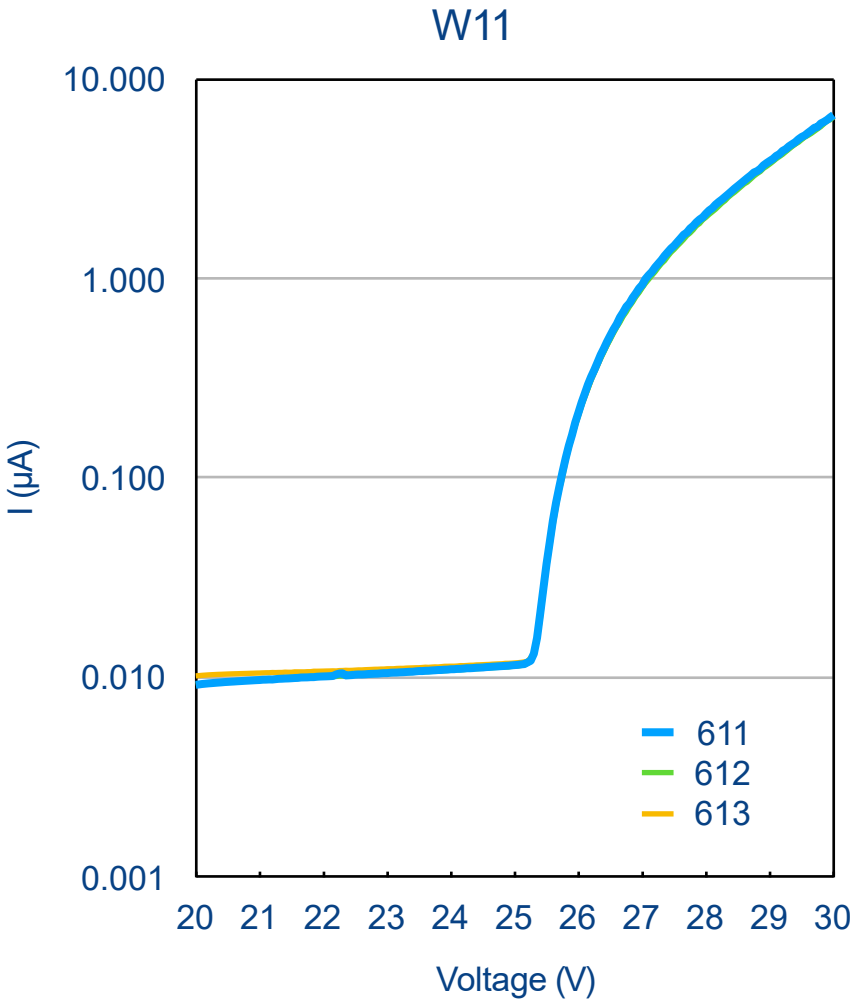
- Recognizing the greater complexity of the SiPM structure, we began with a simpler three-layer filter designed to incorporate a thinned SiNx passivation layer
- The bandpass of this filter is broader than that of a five-layer filter and has less suppression of the slow component

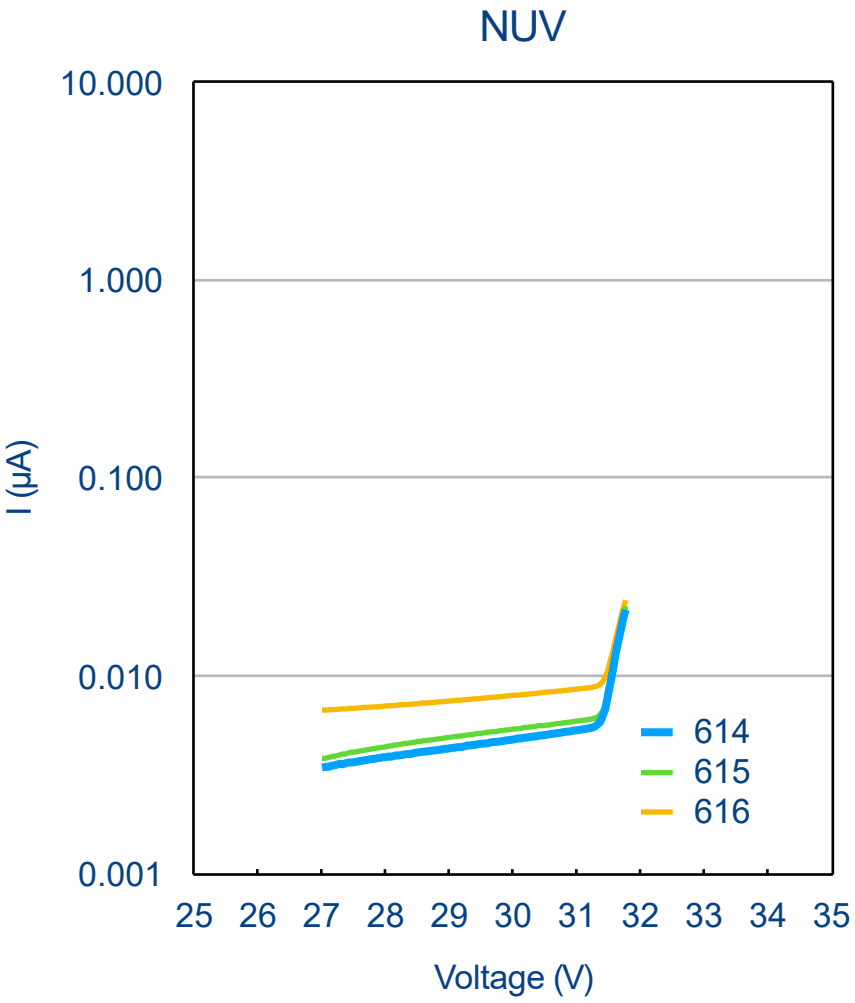


wafer 11

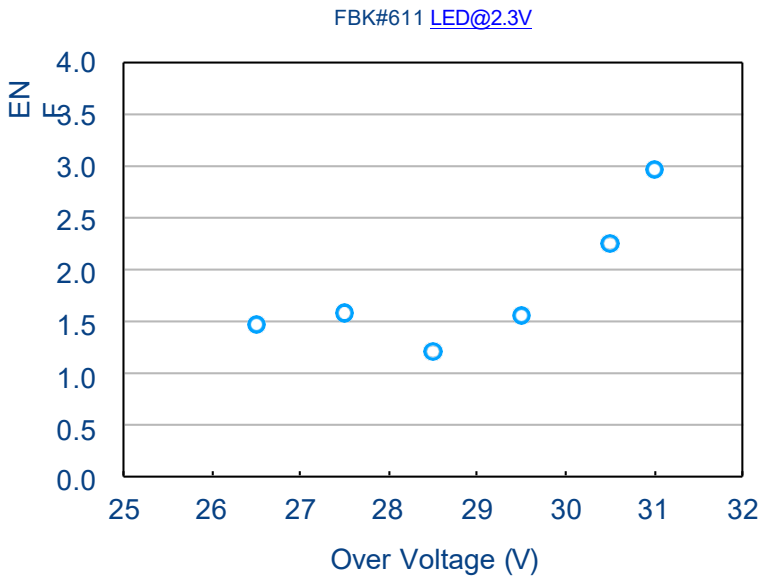


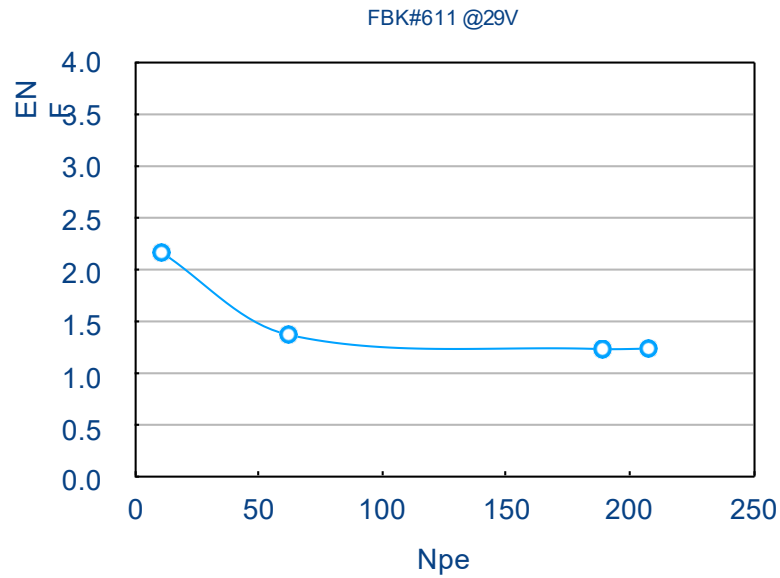
FBK SiPM I-V Curves





Excess Noise Factor: FBK #611



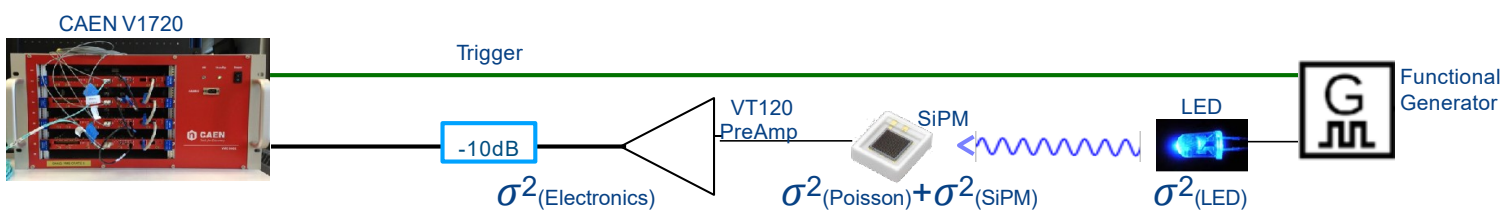


$$\sigma^2_{(observed)} = \sigma^2_{(Poisson)} + \sigma^2_{(SiPM)} + \sigma^2_{(Electronics)} + \sigma^2_{(LED)}$$

$$= N_{pe\,(Poisson)} + N_{pe} \times \sigma^2_{(pe)} + \sigma^2_{(Pedstal)} + \sigma^2_{(LED)}$$

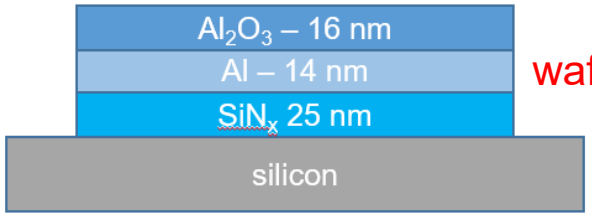
$$= N_{pe\,(Poisson)} \times (1 + \sigma^2_{(pe)} + \sigma^2_{(Pedstal)}/N_{pe} + \sigma^2_{(LED)}/N_{pe})$$

$$ENF = \sigma^2_{(observed)} / N_{pe(Poisson)} = N_{pe(Poisson)} / (\mu_{(observed)}/\sigma_{(observed)})^2 \qquad \because \ \mu_{(observed)} = N_{pe(Poisson)}$$



J. Oyang

FBK SiPM measured performance

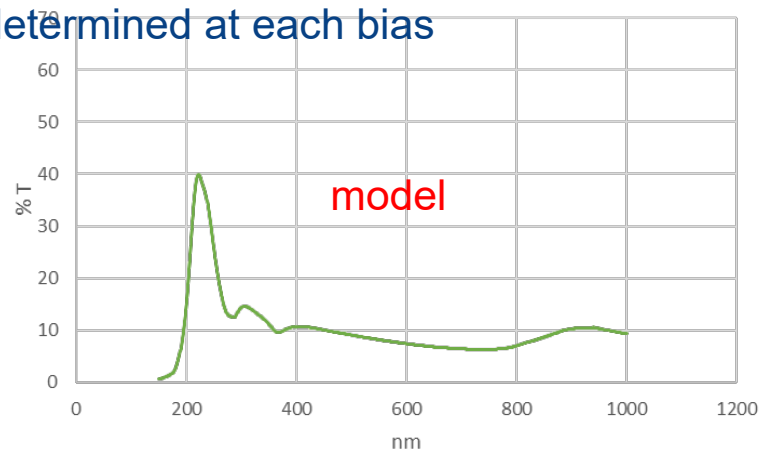


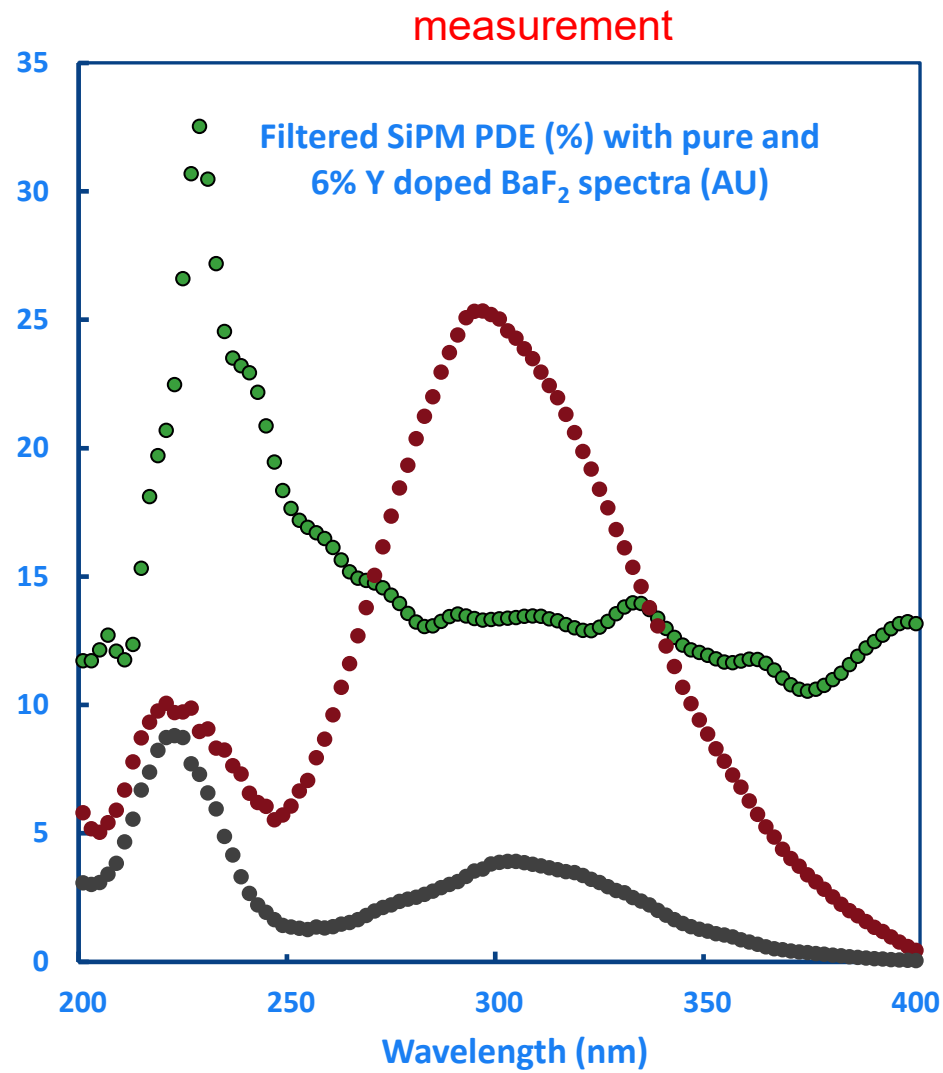
wafer 11

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

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

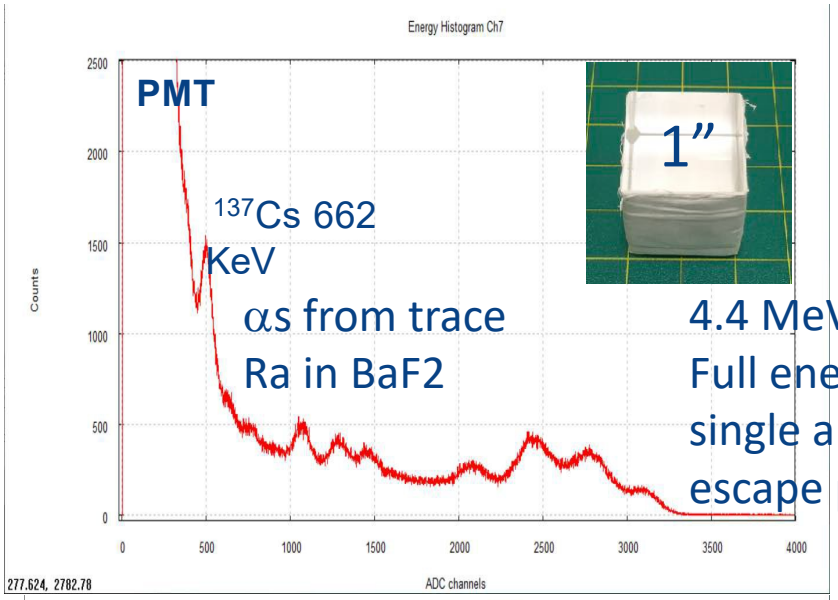
Excess noise factor determined at each bias

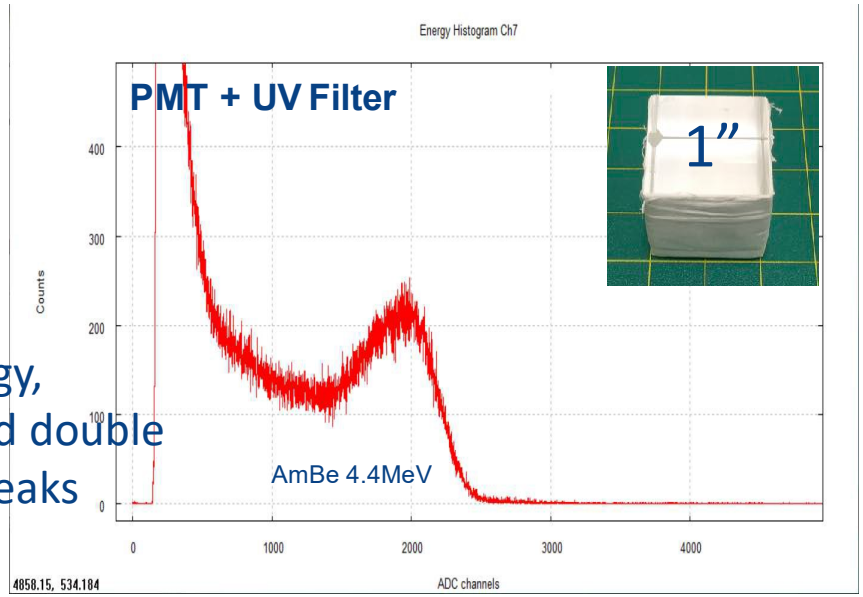


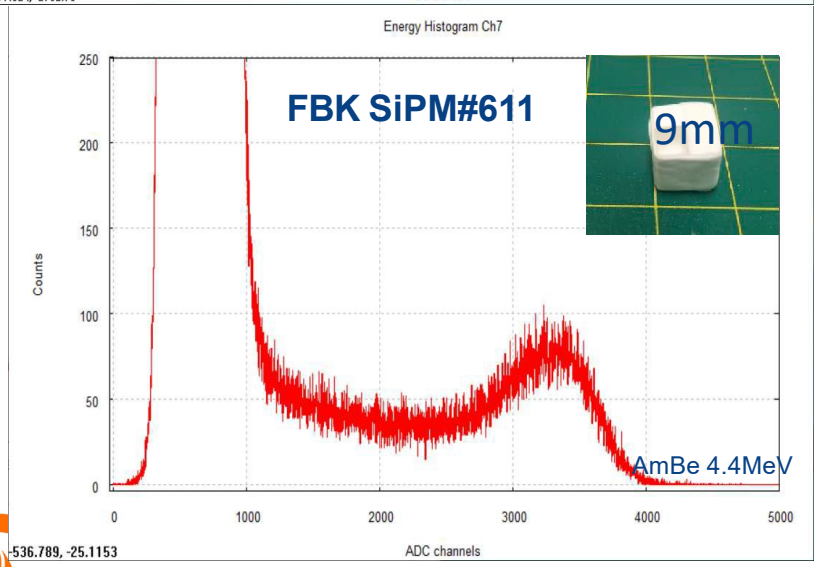


L. Zhang, J. Oyang

BaF_2 + AmBe: PMT and SiPM readout



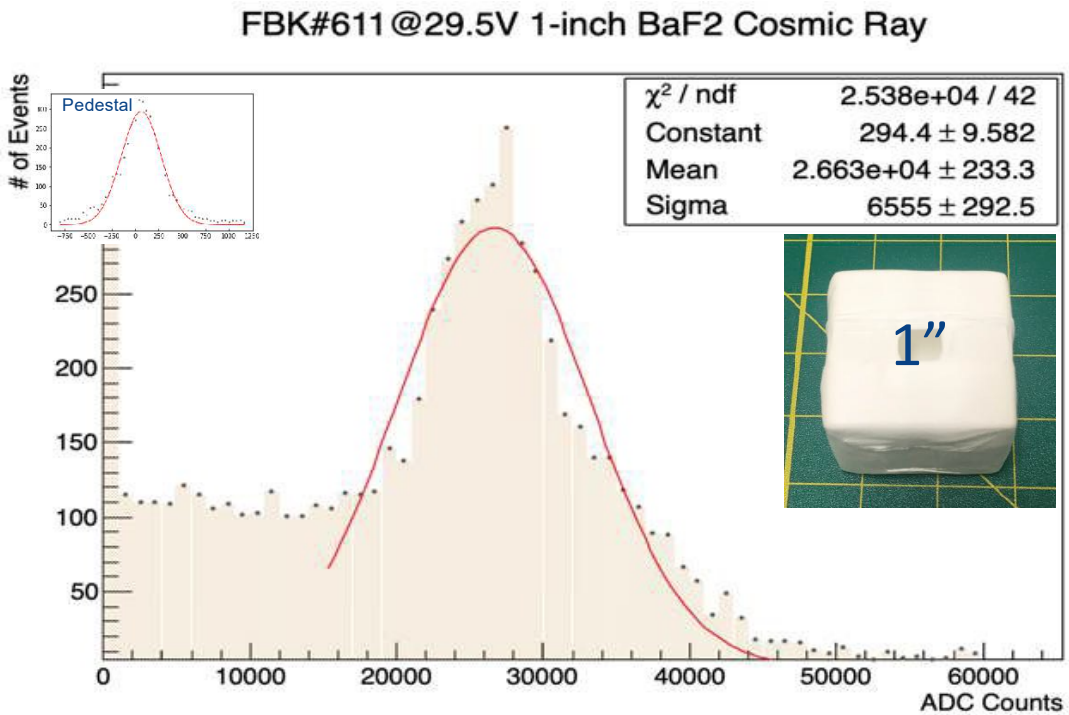




- An AmBe neutron source emits copious 4.4 MeV gammas
- FBK SiPM #611 operated at 29.5V
- BaF_2 dimension 9 x 9 x 9 mm, wrapped with teflon with an opening of 6x6 mm
- 3400 (adc)/29.1(pe/adc) = 117 pe
- 117 pe / 4.4 MeV = 27 pe/MeV

J. Oyang

FBK #611 BaF_2 Cosmic Ray Spectrum

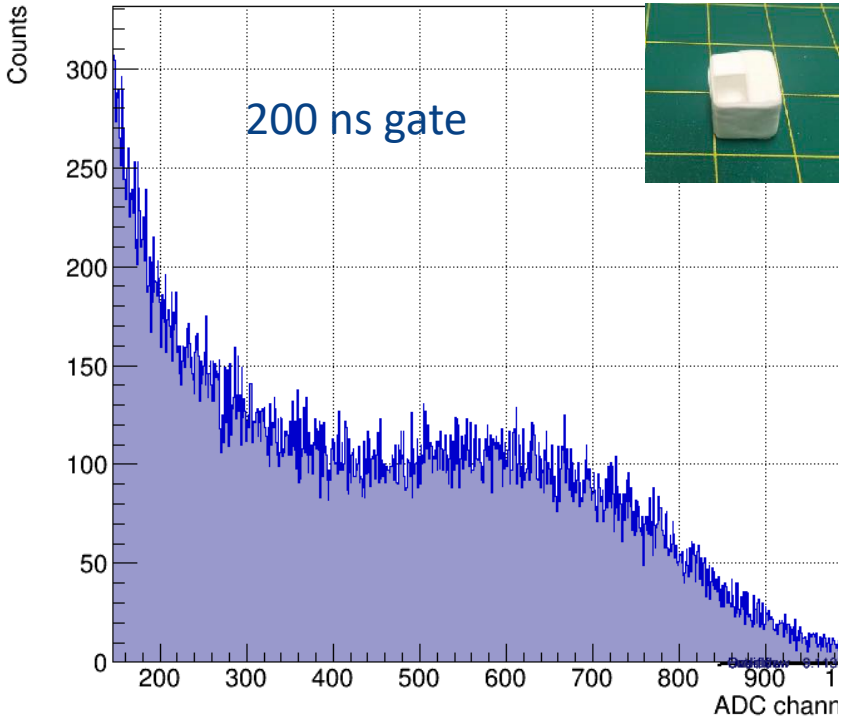


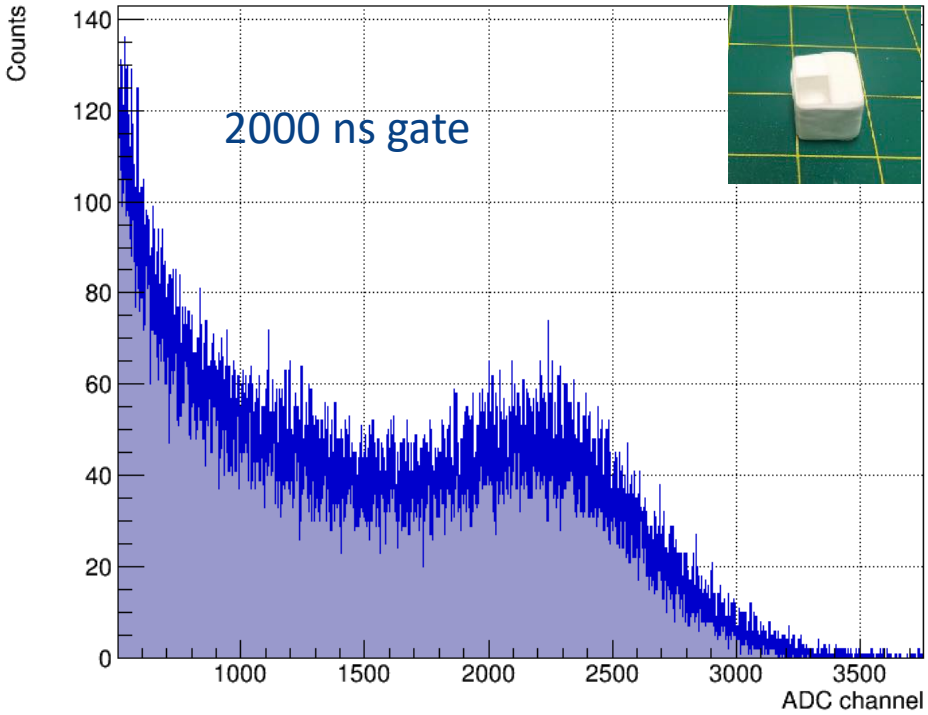
- FBK SiPM #611, dimension 6x6 mm, operated at 29.5V
- BaF_2 dimension 1” x 1” x 1”, wrapped with teflon with an opening of 6x6 (mm)
- Cosmic ray deposits 6.374 MeV/cm * 2.54 cm = 16.2 MeV
- (26631 - 68) adc / 148 pe/adc = 180 pe
- 180 pe / 16.2 MeV = 11 pe/MeV With 2x3 array, expect 60-70 pe/MeV

J. Oyang

SiPM 611 BaF_2 with AmBe source (4.4 MeV)

9 mm BaF_2



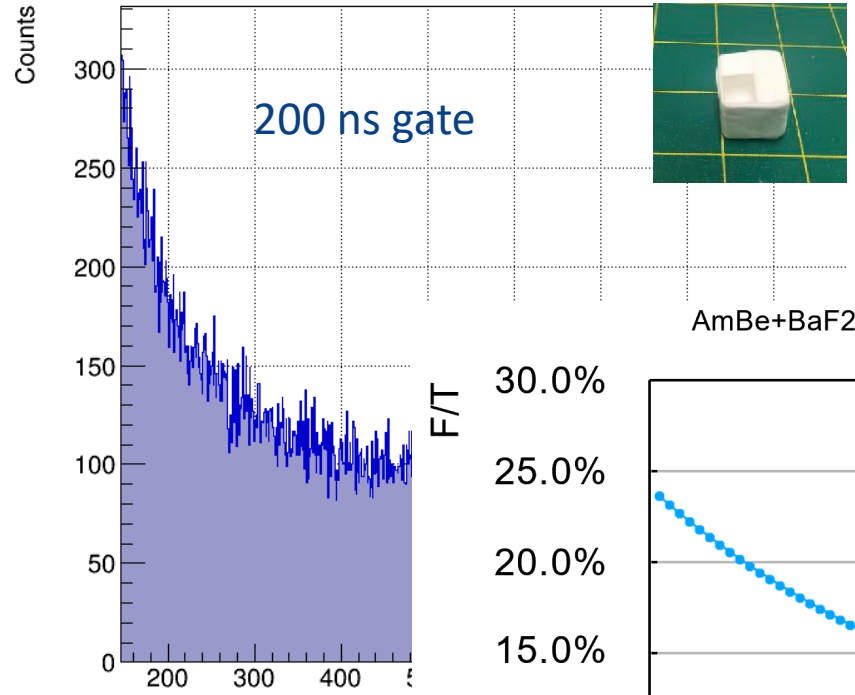


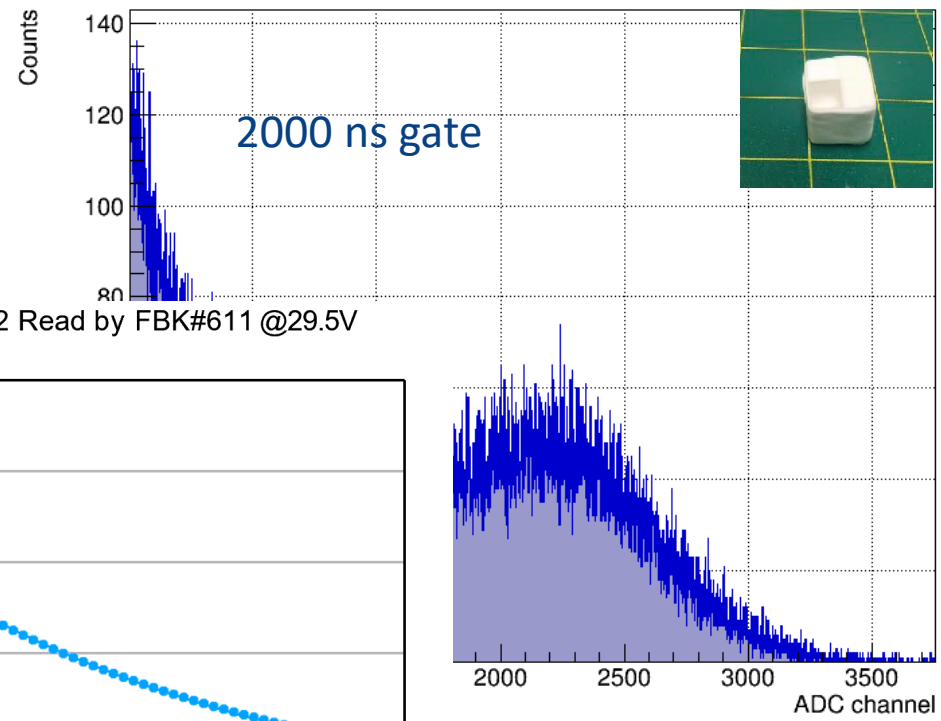
Use of 200 and 2000 ns gates allows extraction of ratio of slow-to-fast scintillation components seen by filtered SiPM: ~4

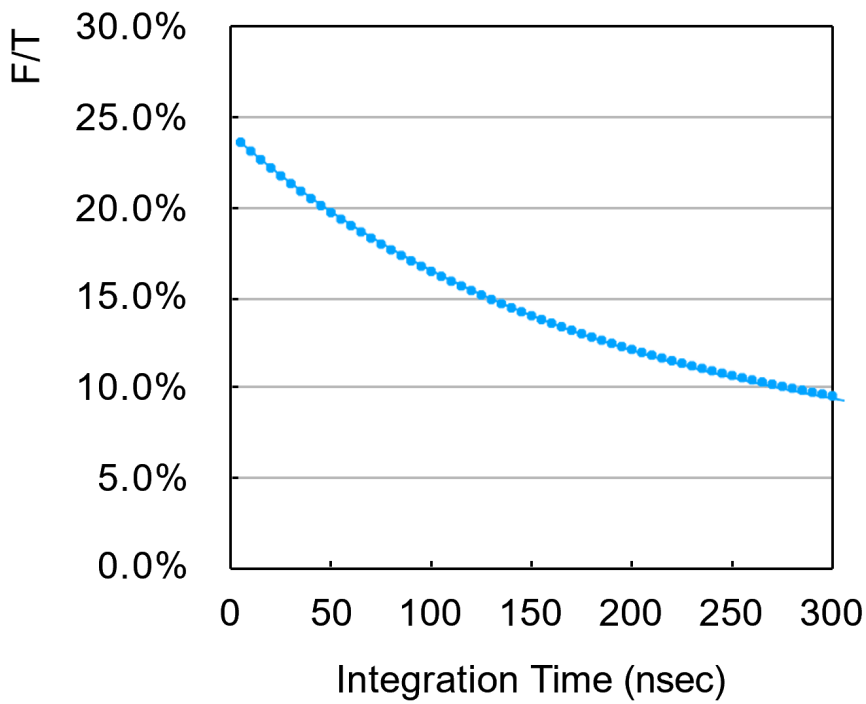
J. Oyang

SiPM 611 BaF_2 with AmBe source (4.4 MeV)

9 mm BaF_2



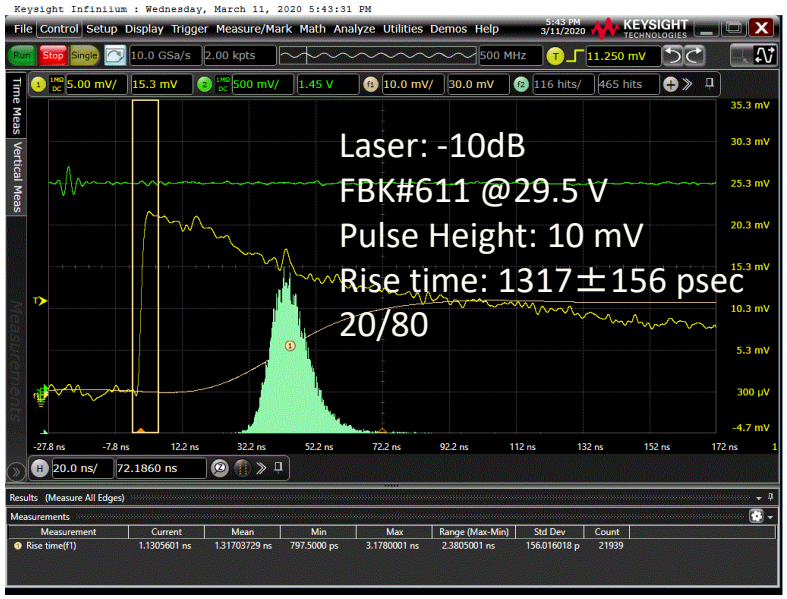




Use of 20(... atio of slow to fast scintillatio

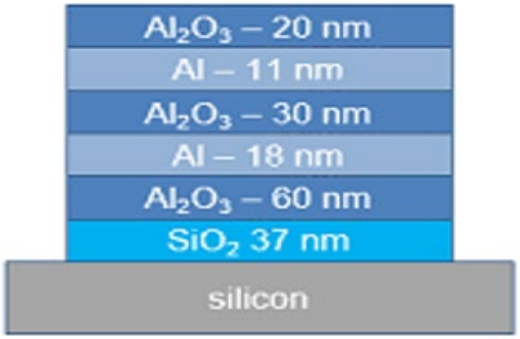
Rise/fall time measurement: FBK #611

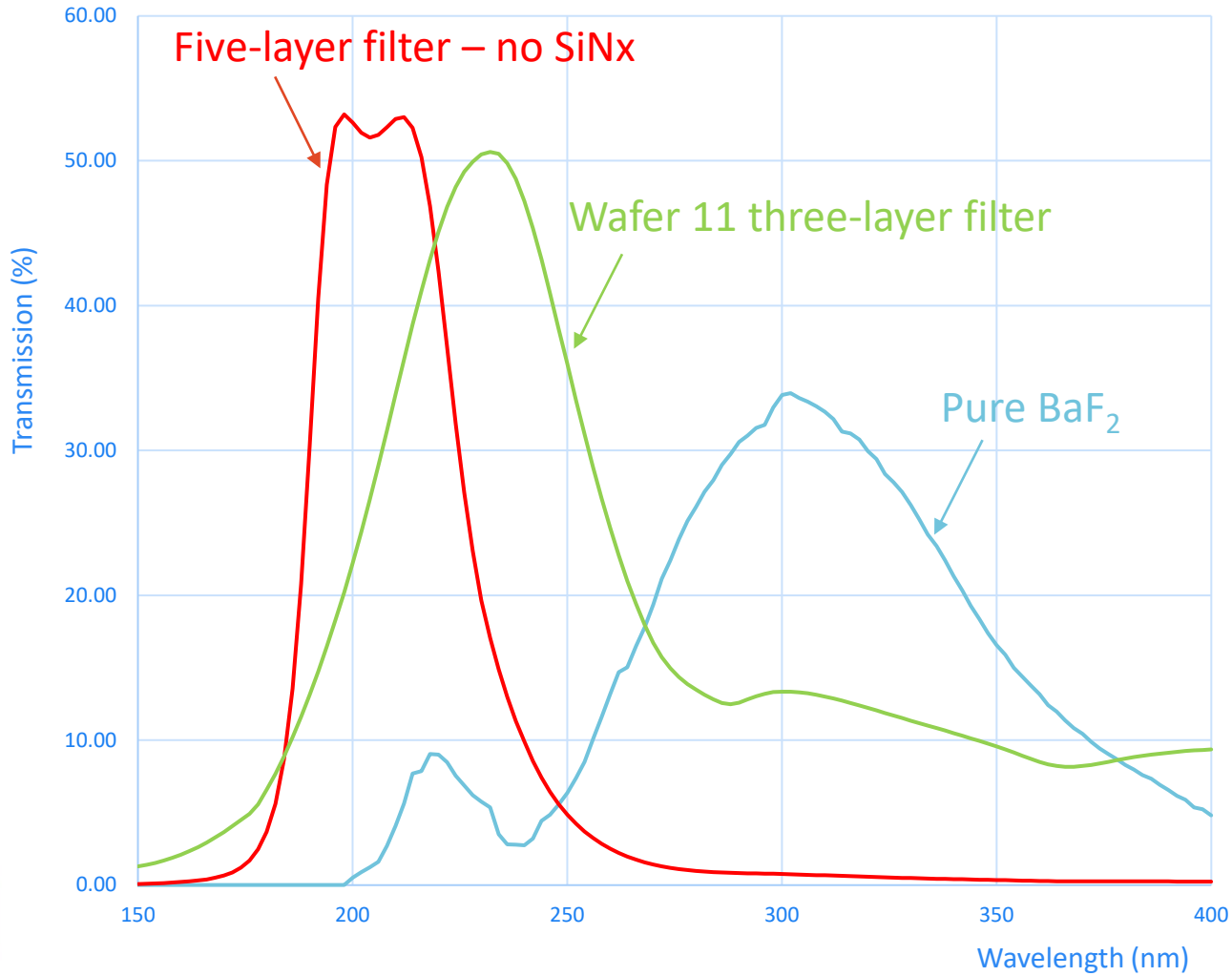
- Measured with a picosecond laser
  - λ = 373 nm
  - Pulse width 21 ps



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





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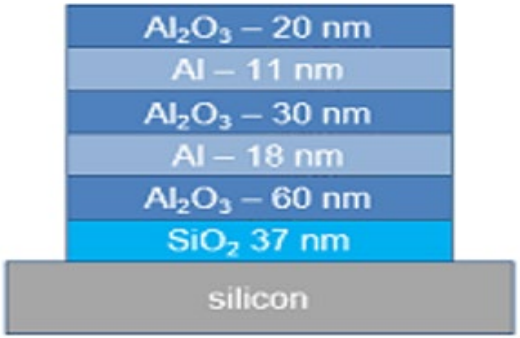

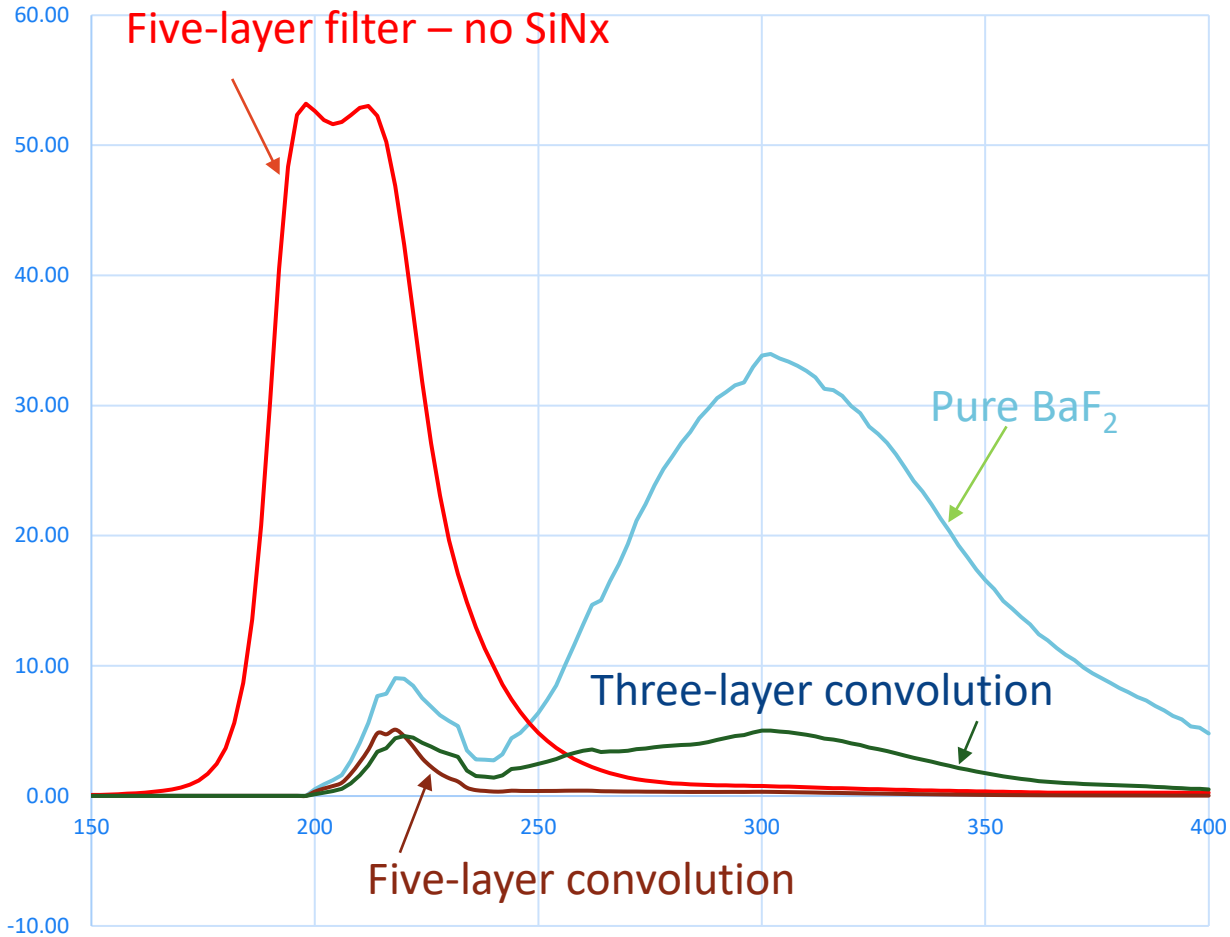

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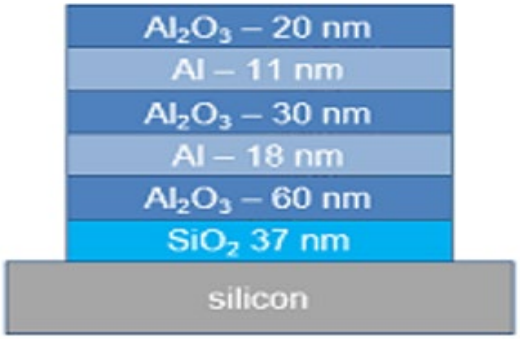
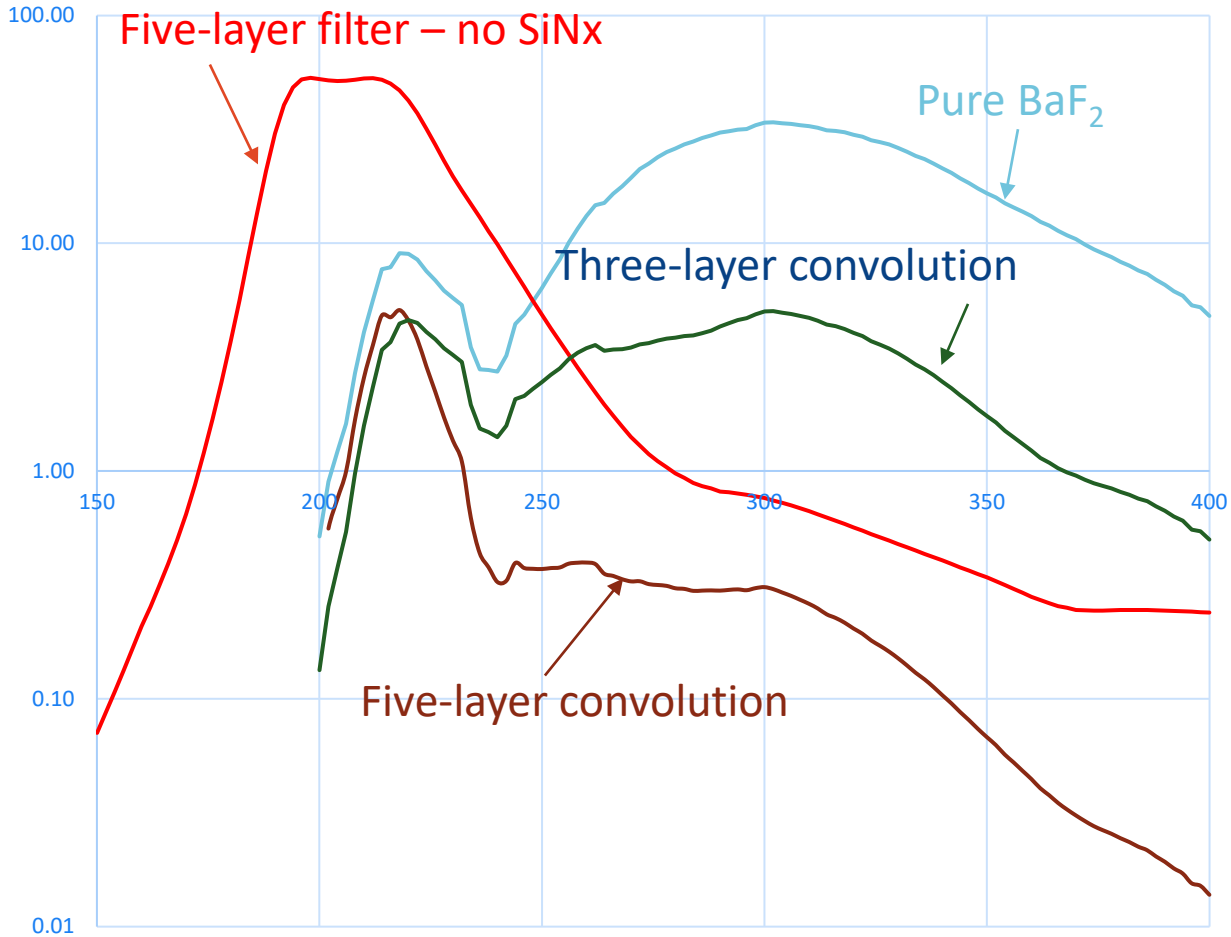
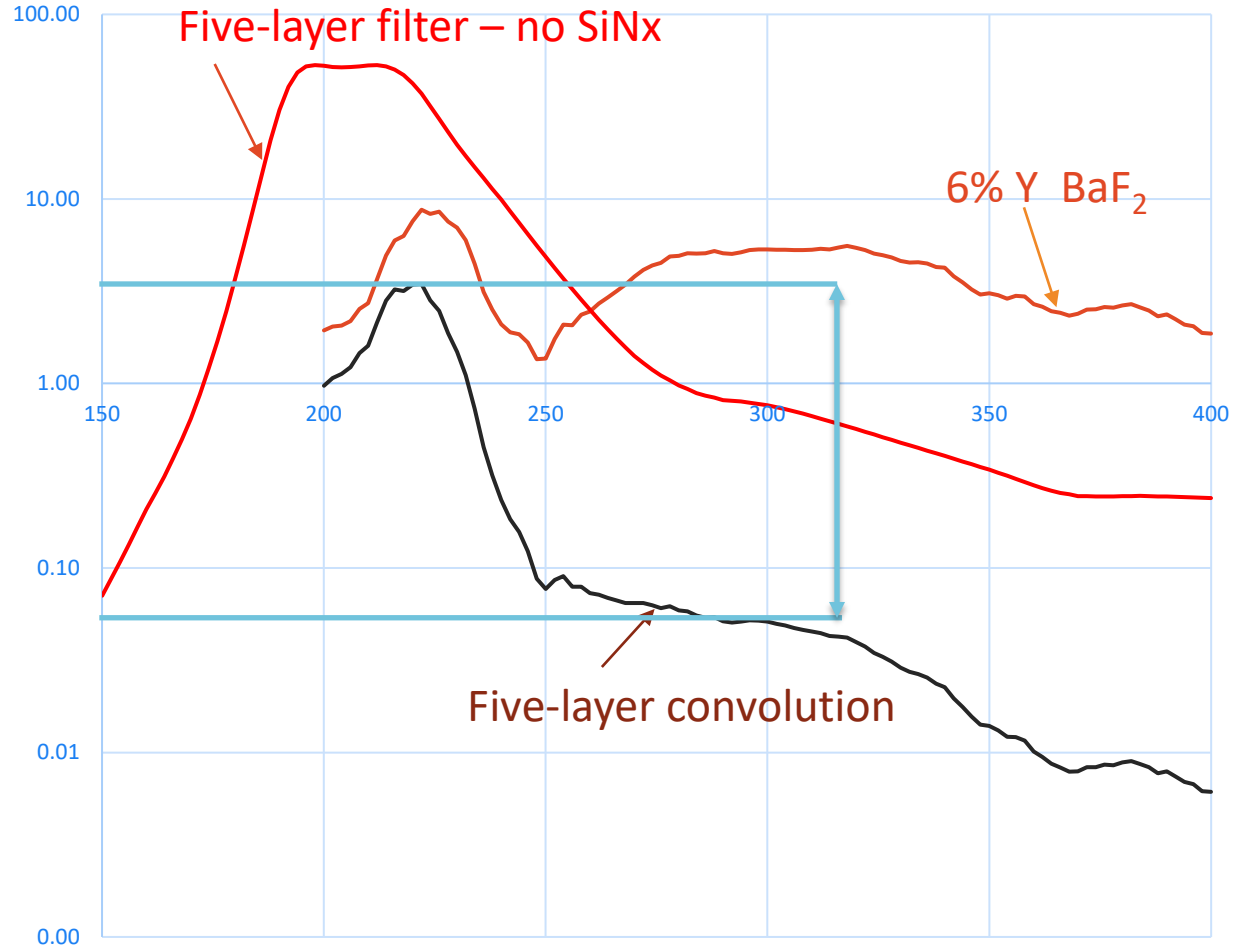




Further improvement of fast/slow performance

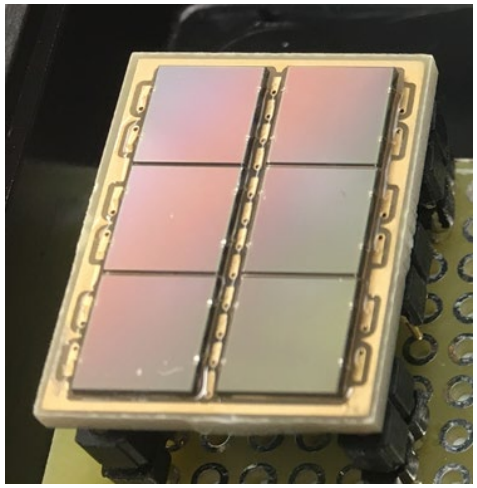
- A system comprising
  - **6% Y-doped BaF_2 crystals**
  - **five- layer filtered SiPMs**

  provides a ratio of fast-to-slow scintillation components that enables high quality electromagnetic calorimetry in high-rate applications such as Mu2e-II



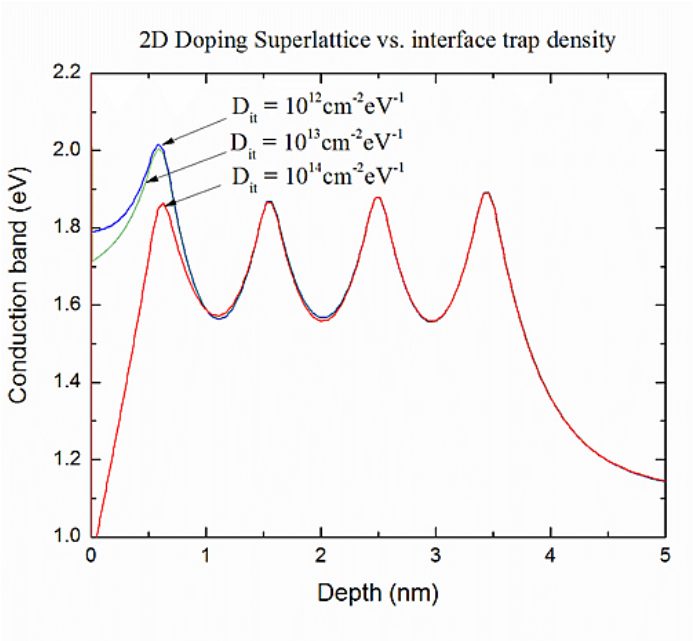
Current status and plans

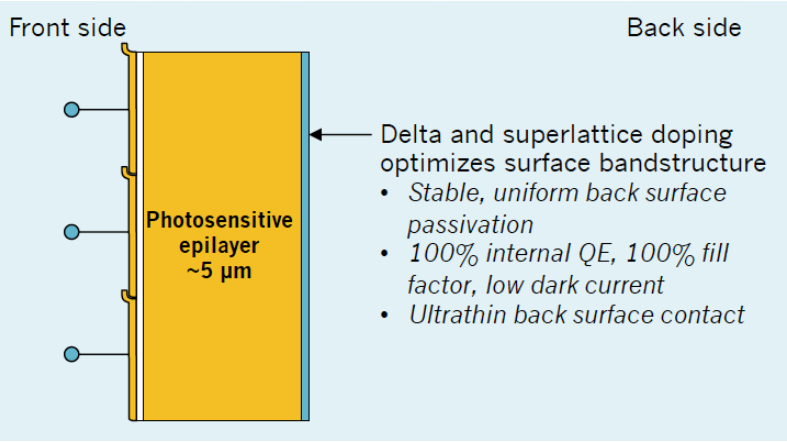
- Next steps in the program
  - Measure spectra with Y-doped BaF_2 crystals to verify the fast/slow scintillation yield
  - Employ 3 x 2 chip array of 6x6mm chips in series/parallel configuration to read out larger crystals – we have samples in hand
  - Measure radiation hardness with γ's and neutrons
  - Burn-in studies for MTF
  - Fab more sophisticated five-layer filters on remaining wafers – this is getting underway as JPL reopens
  - Produce delta-doped superlattice, back-illuminated versions that will have improved QE and timing characteristics



Superlattice structures

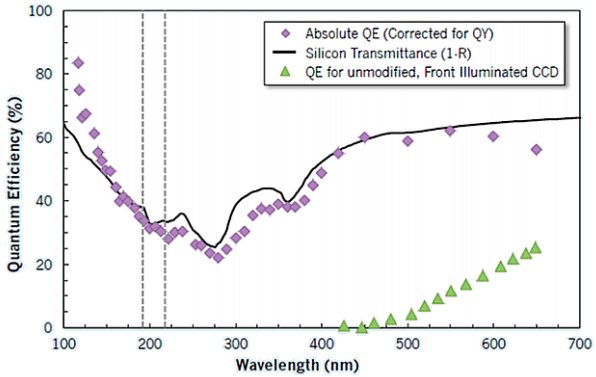
- JPL has developed superlattice (delta-doped) structures that provide enhanced quantum efficiency and improved time response for photosensors
  - Delta-doped superlattices have been successfully employed for many years to enhance the UV performance of CCDs and APDs used in UV astronomy in satellites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



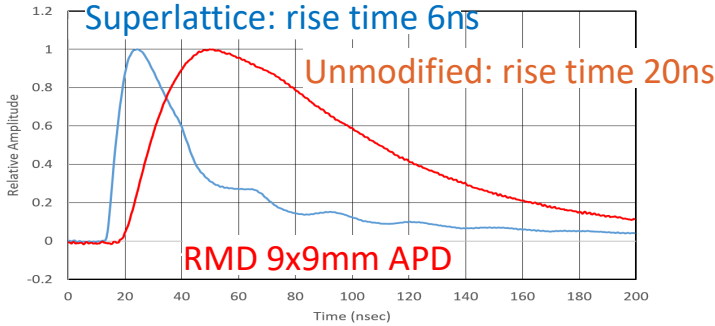


What does the superlattice do?

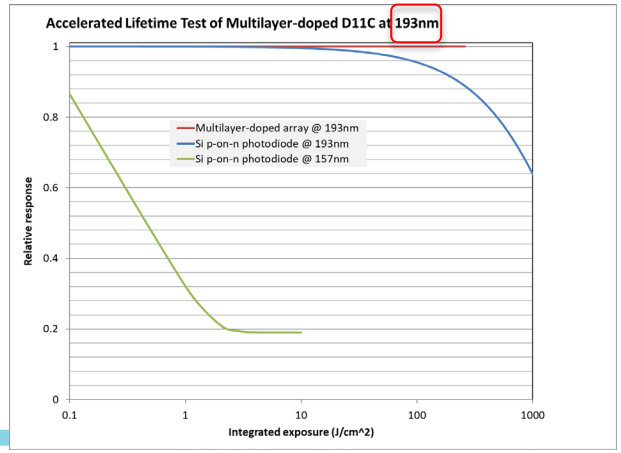
- Recombination of photoelectrons is suppressed by quantum exclusion, resulting in close to **100% internal QE**
  - Quantum efficiency in the 200-300 nm region approaches the silicon transmittance (1-R) limit



- Elimination of the undepleted region before the avalanche structure **substantially improved time performance** over a normal 9mm RMD APD This should work with SiPM structure as well
  - Both rise time and decay time were improved



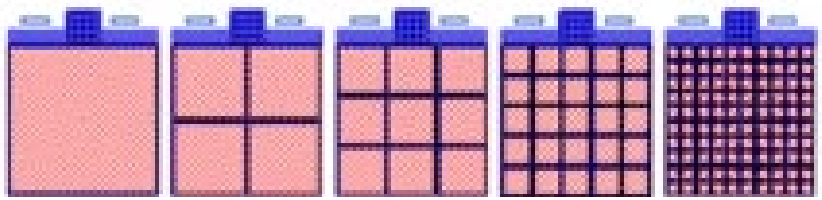
- The superlattice structure provides **stability under intense UV illumination**
  - Relevant regime for Mu2e-II is ~ .1-10 J/cm^2 of 200 -300 nm UV (~ 4-6 eV)



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

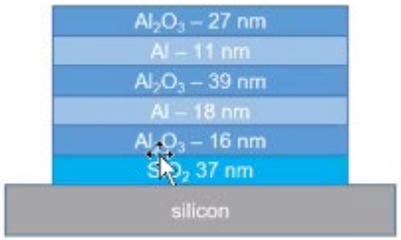
Next steps in the program

1. **Optimization of the MBE superlattice layer parameters**
   - In order to decouple the details of fabricating surface structures from the avalanche structures, this will first be done on a photodiode (*i.e.,* no gain)
   - A superlattice will be added to diode structures with SiPM-like layouts of different area, in order to evaluate the relative contribution of surface and volume leakage currents

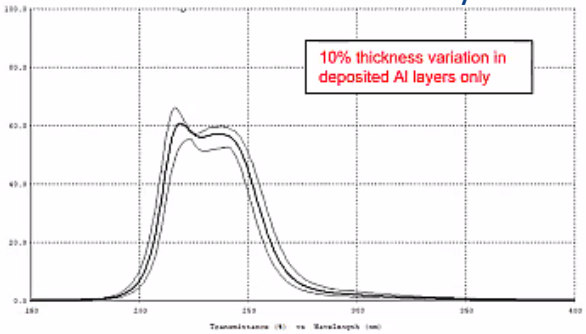


500 250 167 100 50μm

2. **More complex filters will be incorporated**



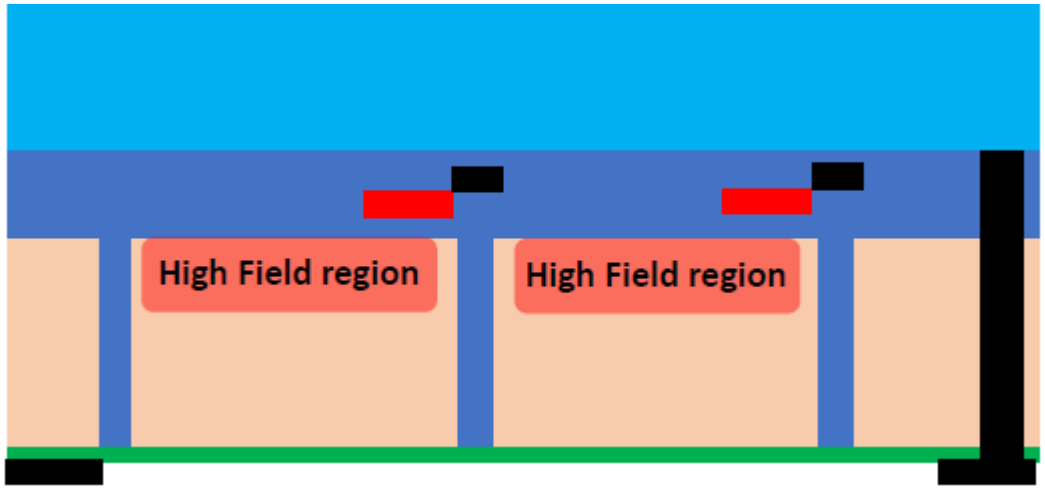
Process variation study



Next steps – the ultimate goal

3. Backside illuminated SiPM with optimized superlattice

- 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

Conclusions

- A barium fluoride crystal calorimeter that exploits the fast scintillation component for its high-rate capability and excellent time resolution is an important component of high-rate experiments such as Mu2e-II and could improve volumetric resolution in PET as well
  - Y-doped BaF_2 provides very significant suppression of the 320 nm slow component with little effect on the 220 nm fast component
  - In order to fully exploit the 0.6ns decay time of the fast component for improved rate capability and time resolution, a UV sensitive filtered SiPM is required and is under development
- Desired device characteristics
  - High gain ✓
  - Good PDE for the 220nm BaF_2 fast component ✓
  - Rejection of the 320nm BaF_2 slow component ✓
  - Excellent rate performance
  - UV stability
  - Radiation hard to gammas, neutrons and UV photons
- We are building on the initial success towards a fully capable device

MCP PMTs for BaF_2 – an aside

- Microchannel PMTs at first glance seem like an attractive photosensor for BaF_2 readout
  - Large area
  - High gain
  - Work in a magnetic field
  - Capable of 30ps timing
  - With ALD coating, there is a factor of two gain reduction at 5 C/cm^2 collected at the anode
  - Barium fluoride scintillation emits 12,000 optical photons/MeV (fast+slow component)
    - A 10 krad exposure (100J/kG) to a 3x3x30 cm^3 crystal produces 75 x 10^{18} photons, or 23 x 10^{16} pe at 10% geometric and 30% photocathode efficiency. With a 9 cm^2 cross section and a gain of 10^6, this is ~1.7 x 10^4 C/cm^2 collected at the anode
    - Thus, MCPs are not suitable for readout of scintillating crystals in a high-rate environment