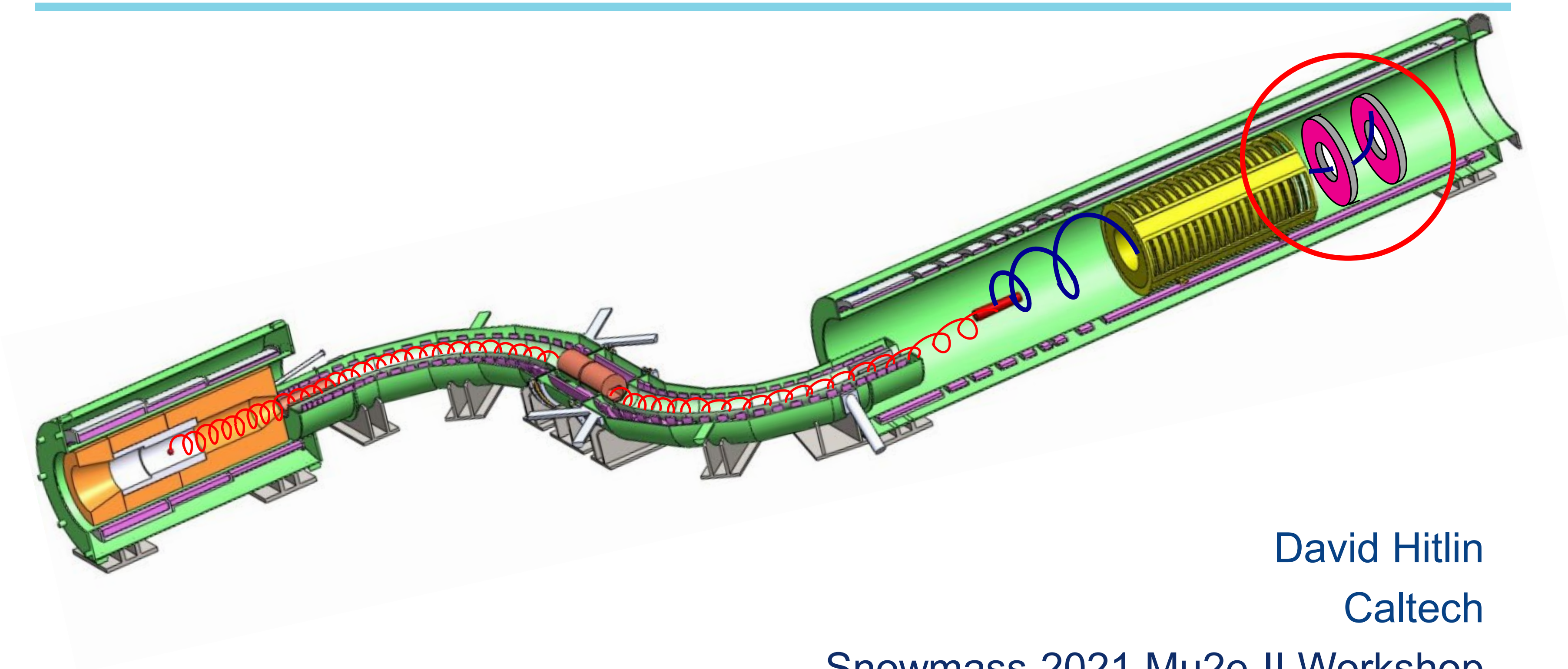
Progress on a photosensor for the readout of the fast scintillation light component of BaF_2

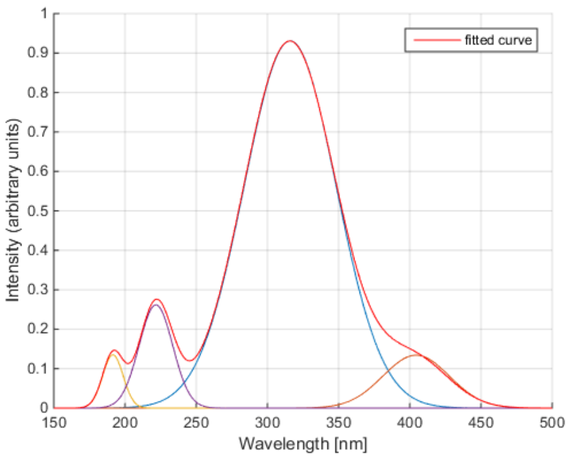


David Hitlin
Caltech

Snowmass 2021 Mu2e-II Workshop
September 22, 2020

Photosensor options for BaF_2 readout

- 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 fast component 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

  Suppress the BaF_2 slow component by Y doping, as developed by Zhu *et al.*,: a major advance, although R&D remains to be done

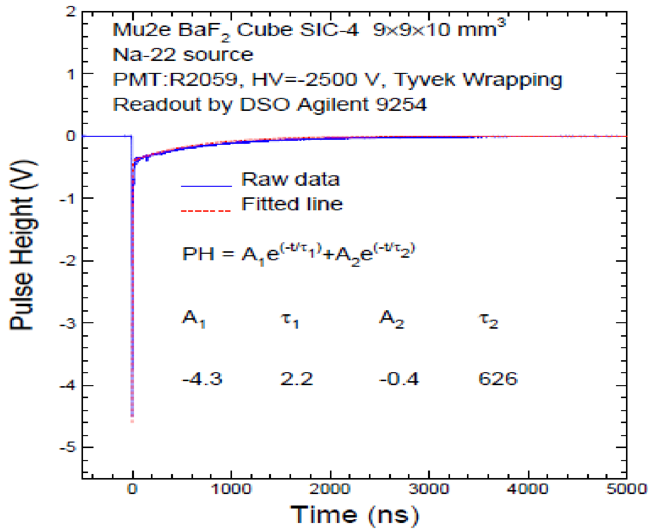
  Develop a SiPM that is sensitive only to the fast component

  This is being done by a Caltech/FBK/JPL group

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

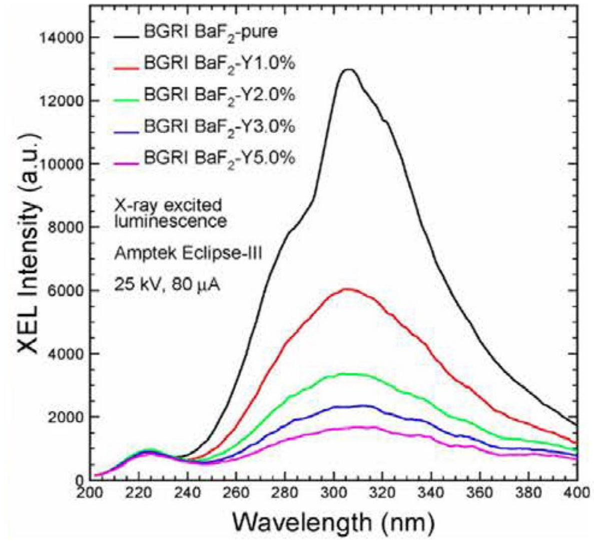
Pure and doped BaF_2

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

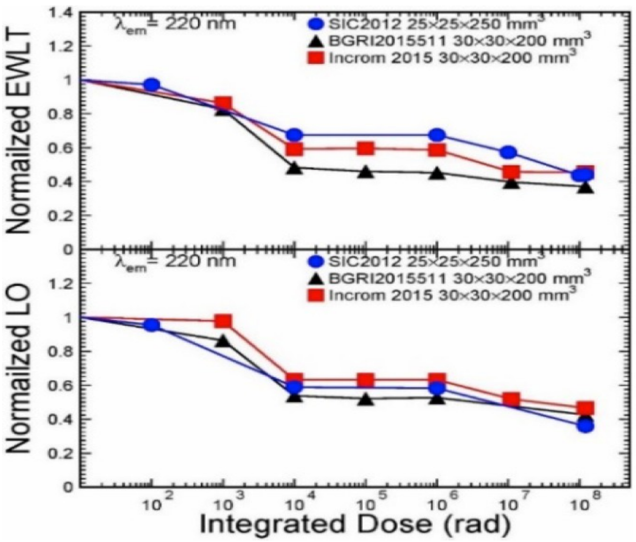


R.-Y. Zhu.
CPAD 2019

Y doping can suppress slow scintillation component



Radiation hardness

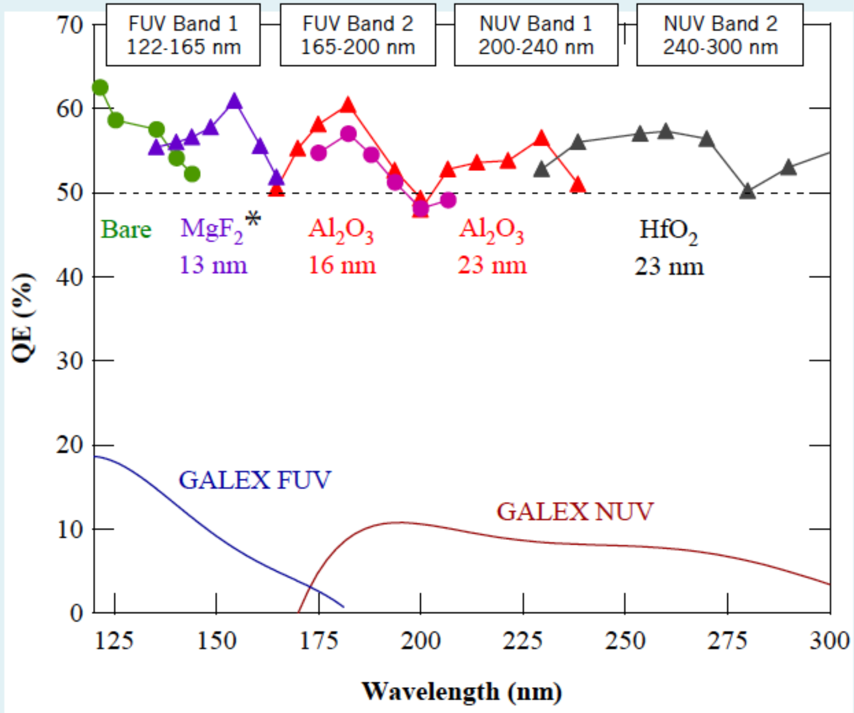


CIT/FBK/JPL SiPM - a phased approach

- Building on our experience with a large area APD developed with RMD, we have adopted a phased development approach
  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
  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 present results from the first 6x6mm chip
  - 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 planned the next rounds of R&D, which will provide an improved filter, UV tolerance and improved time response

ALD antireflection filters improve QE

AR Coatings for UV Detectors



*MgF_2 result for thermally evaporated film

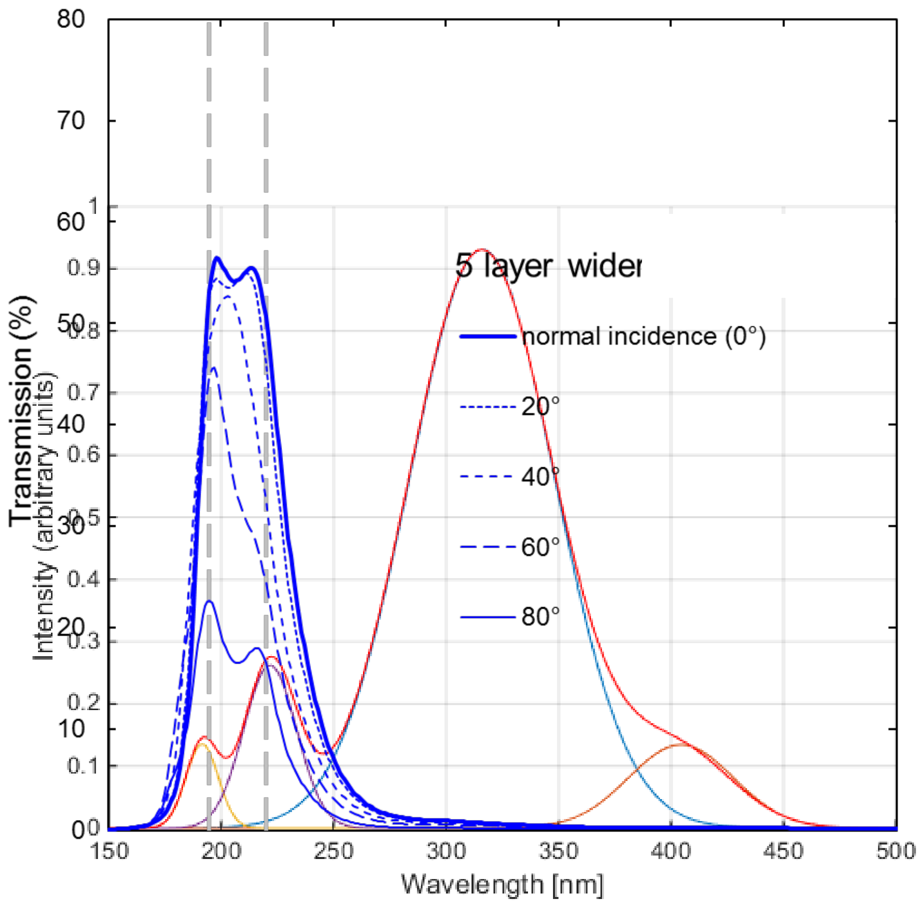
ALD-AR coatings provide up to **2X improvement** over uncoated baseline and a **5x-50x improvement** over incumbent UV detector technology

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

The ALD technique can also be used to make a bandpass filter

ALD bandpass interference filters

- A five layer filter encompass 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

Passivation layer on which the filter is constructed is SiO_2

ALD bandpass interference filters

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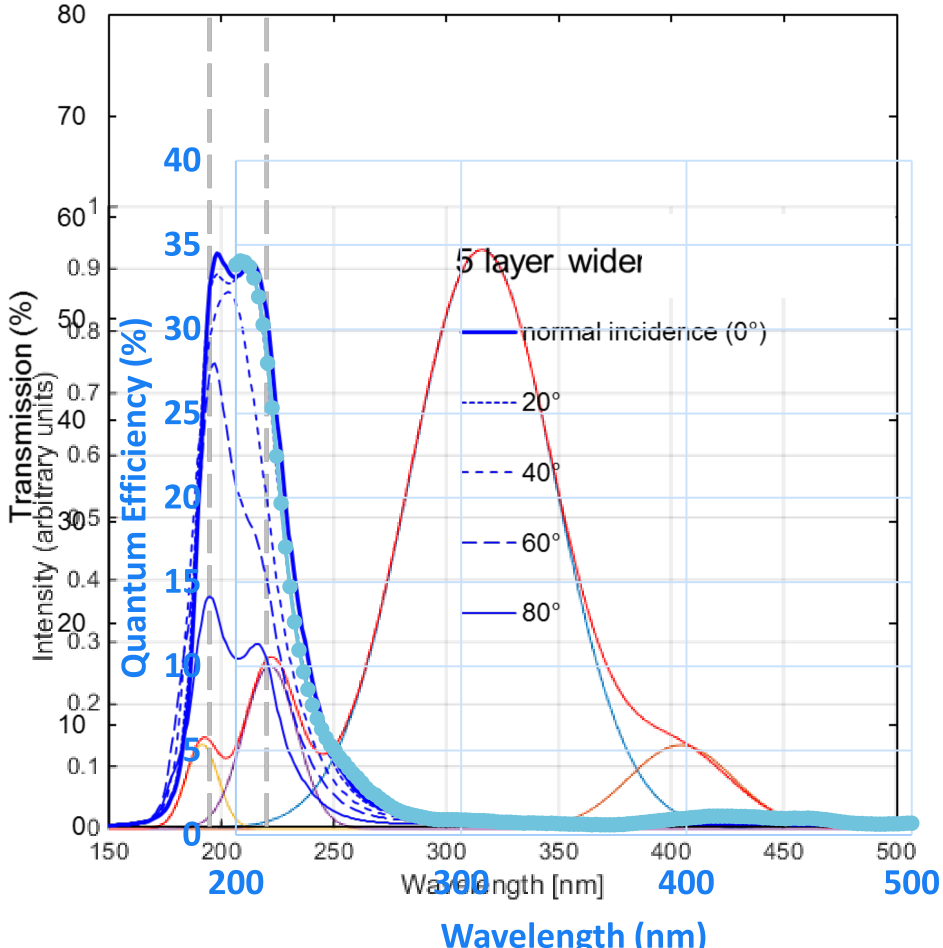
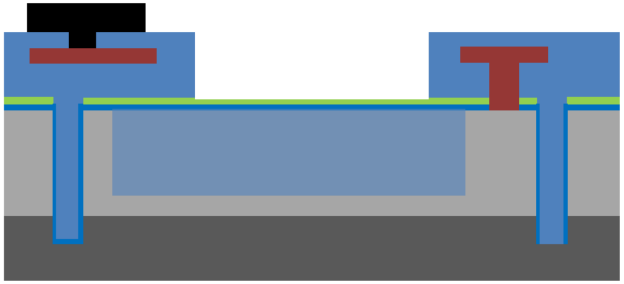


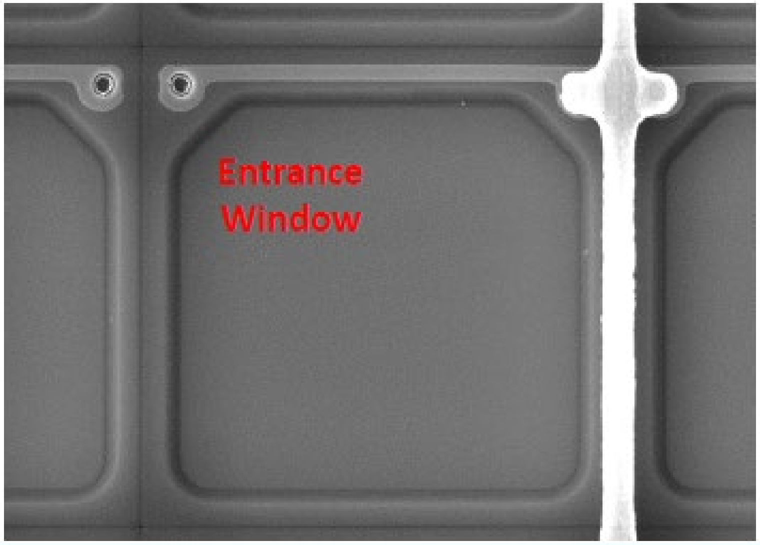
Measurement scaled using a model to QE at nominal gain/bias

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

SiPM fabrication and test

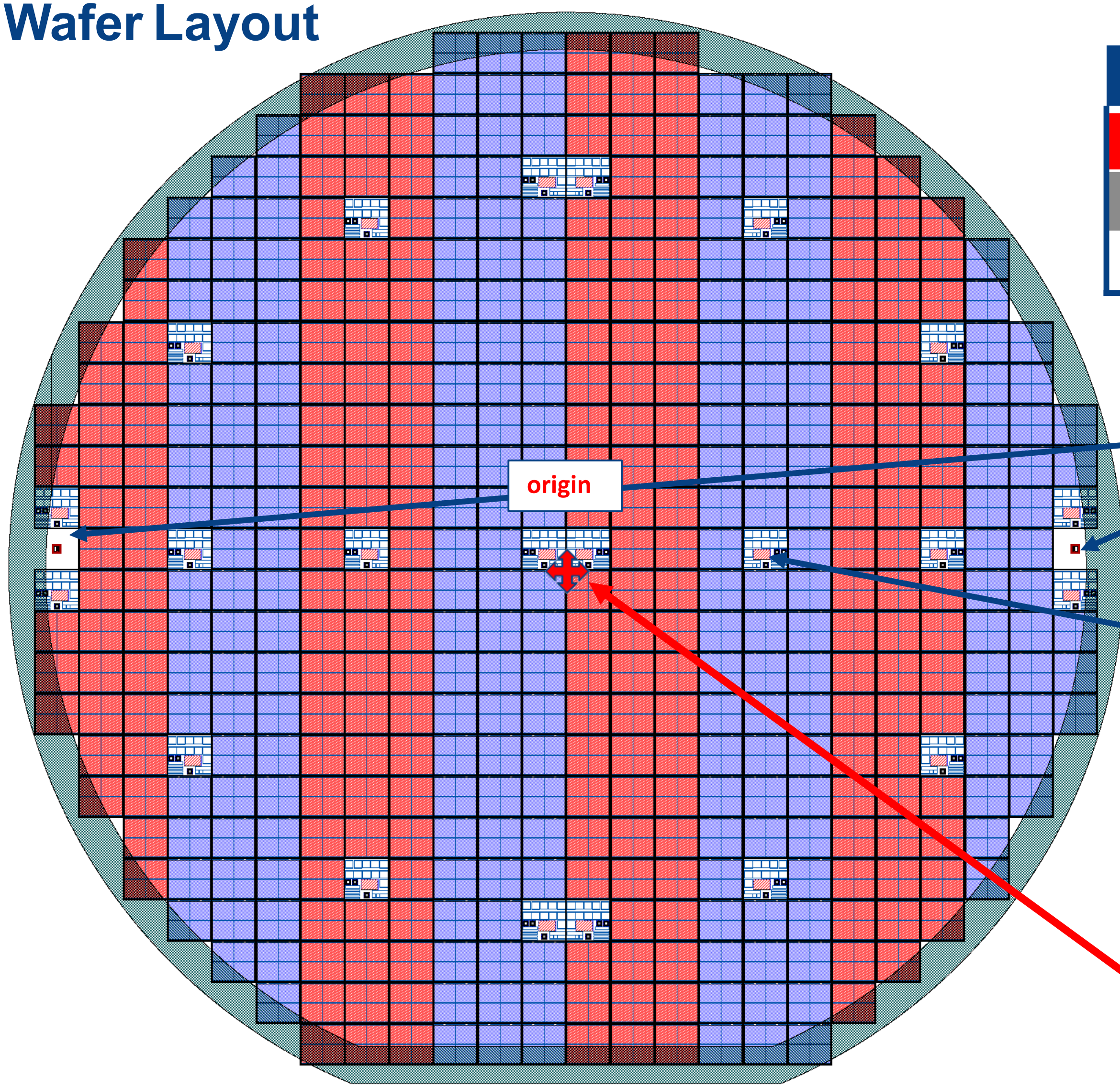
- FBK has fabricated wafers based on current NUV designs, with various modifications, including guard ring structures
- FBK thins or removes SINx passivation layer
- ALD filters are deposited at JPL
- The wafers are returned to FBK for probing and dicing into chips
- 6x6mm devices with three layer filters have been fabricated and tested at Caltech
  - Filter performance and PDE as a function of wavelength have been measureed 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, slow fast scintillation yield





Wafer level production and processing

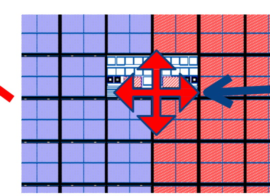
Wafer Layout



	Structure	#
(red)	35um_std	231
(grey)	35um_RqM	231
	Test Structure	22

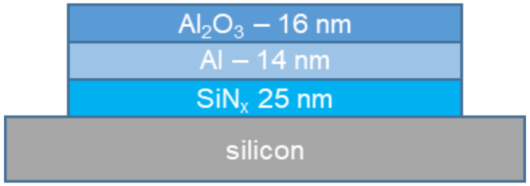
Mask alignment markers
(Filter etching as post-processing step)

Test Structures

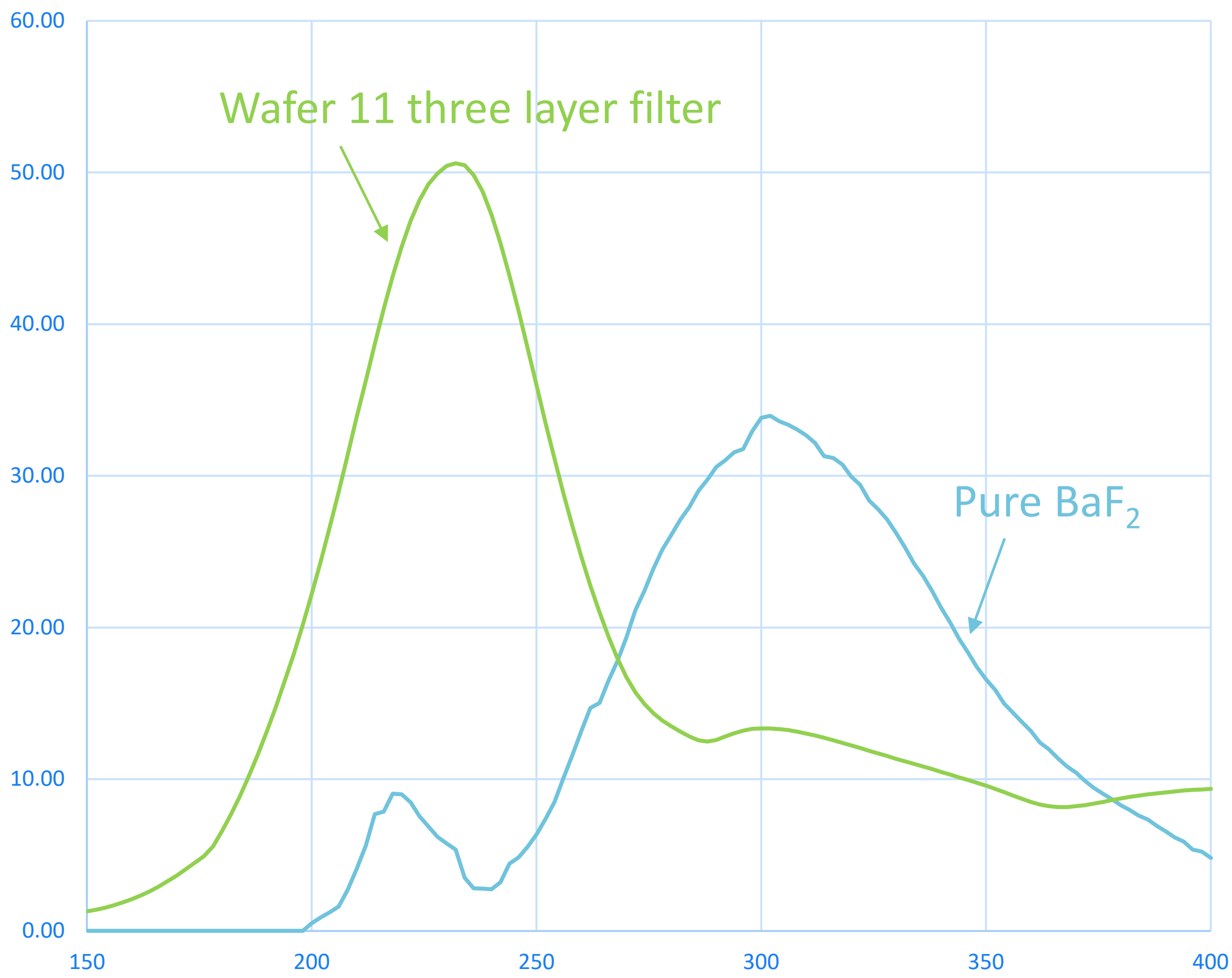


Initial SiPM filter uses three layers

- 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



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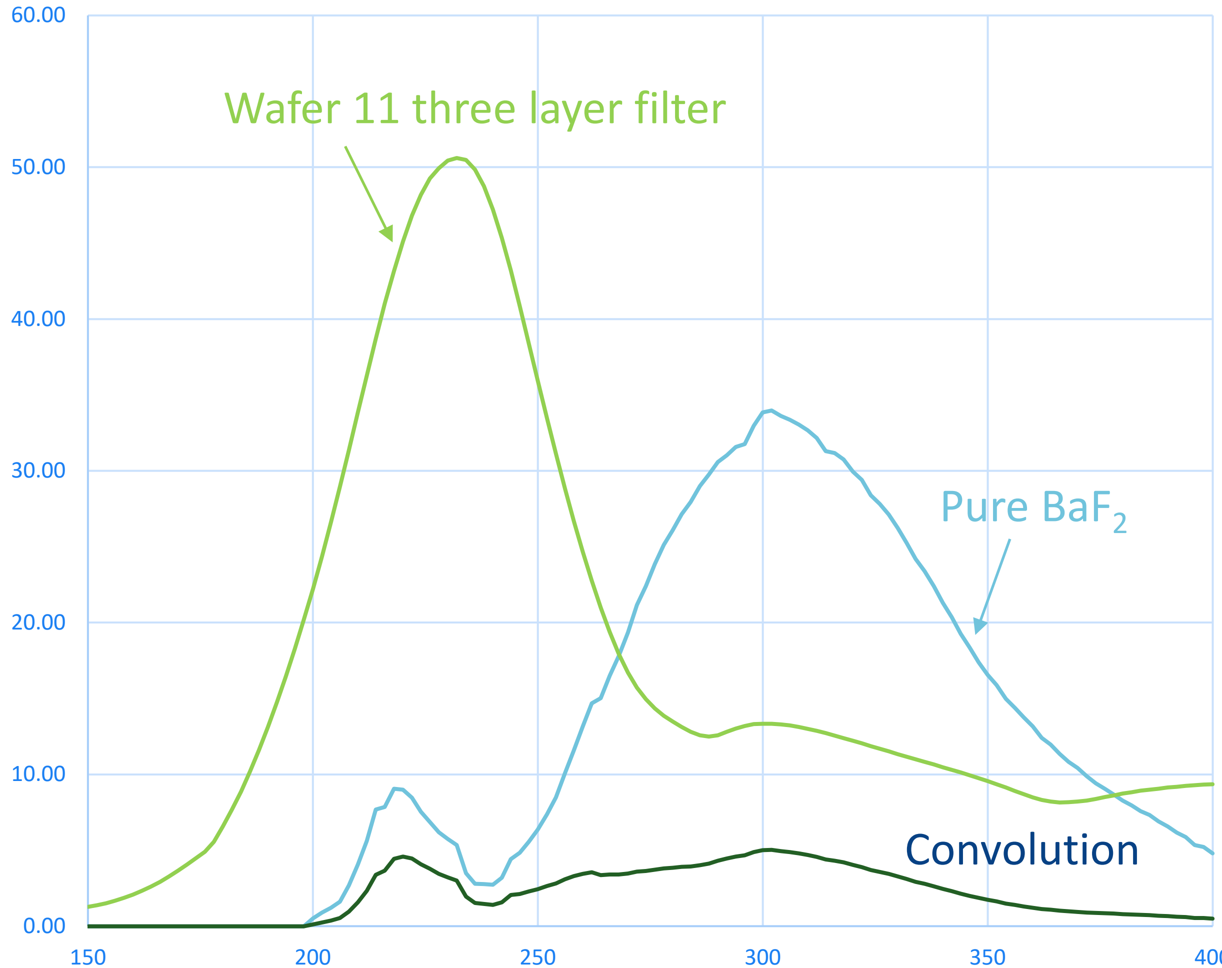
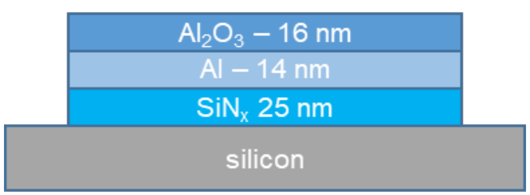
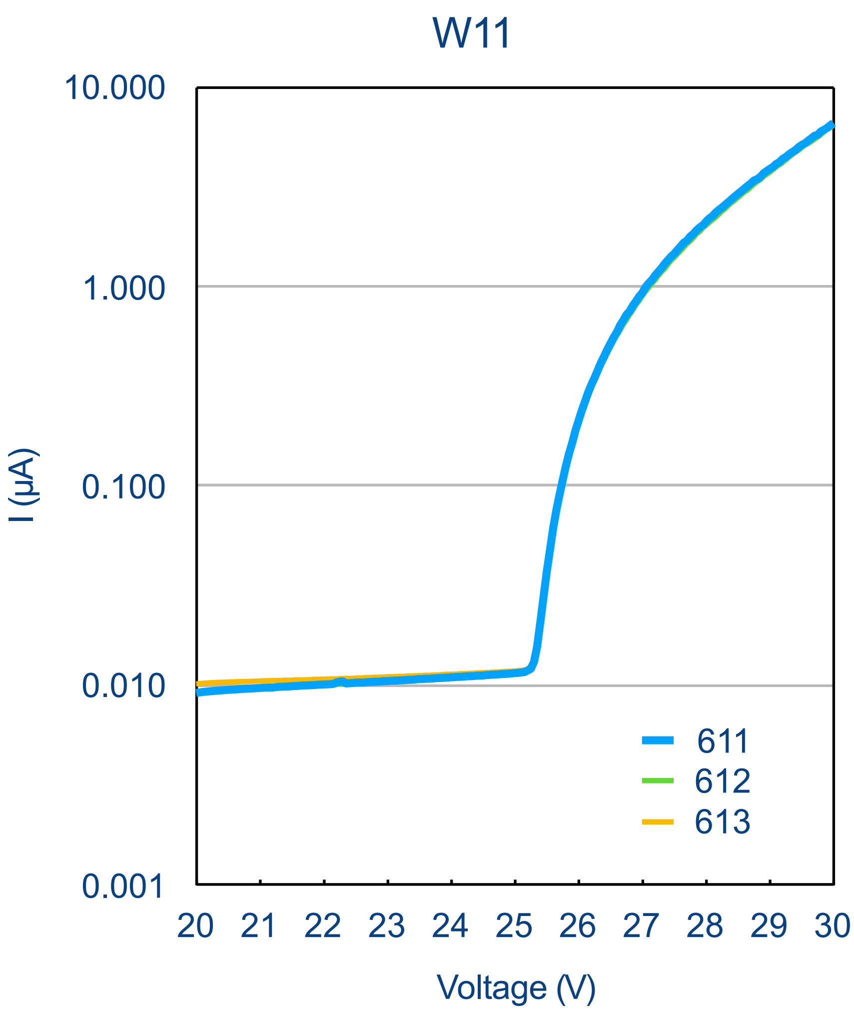
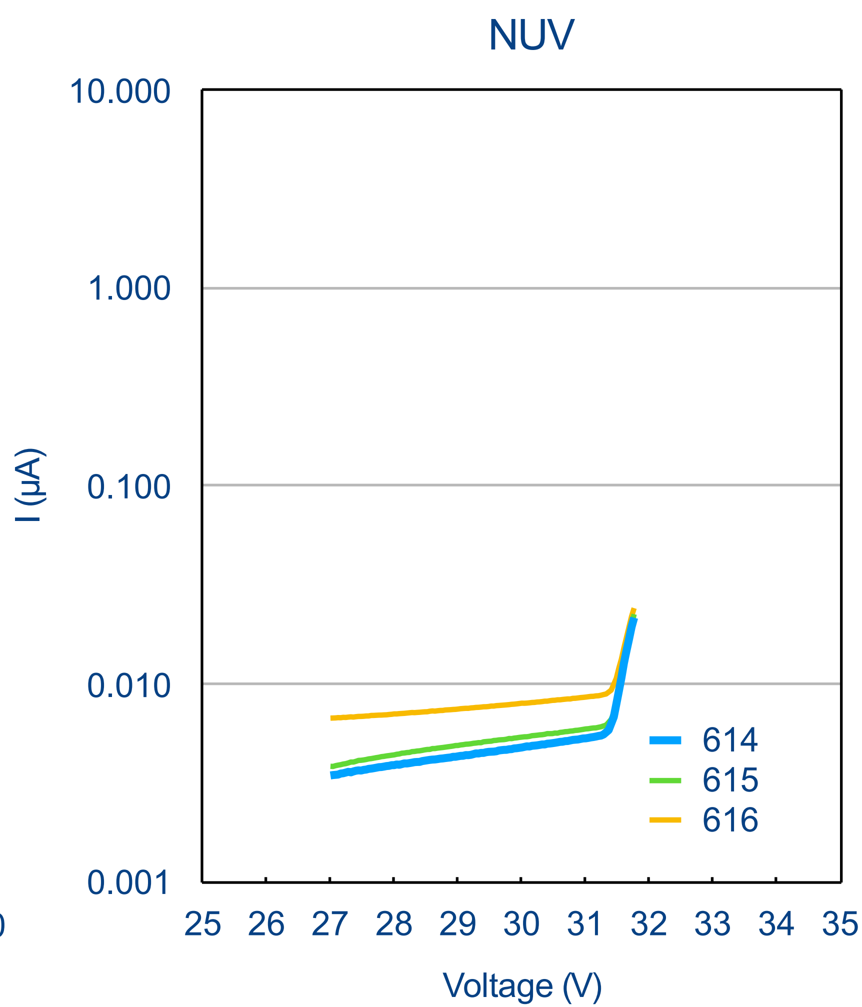




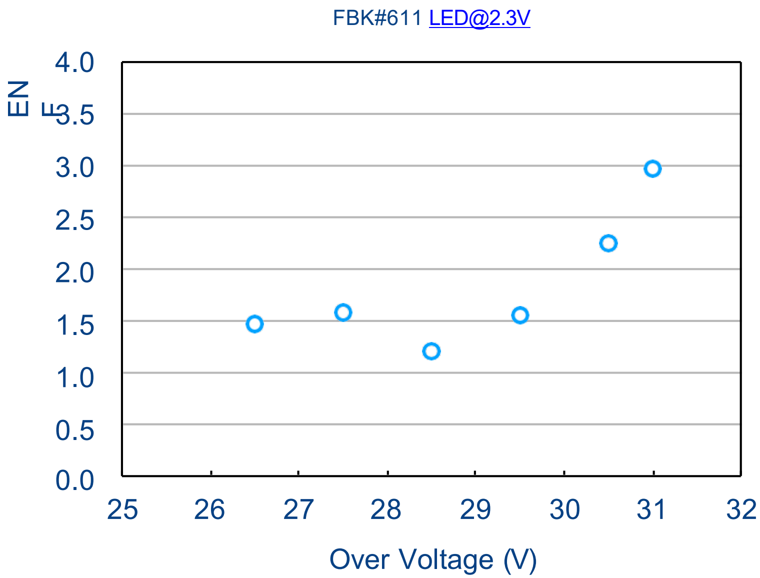
wafer 11

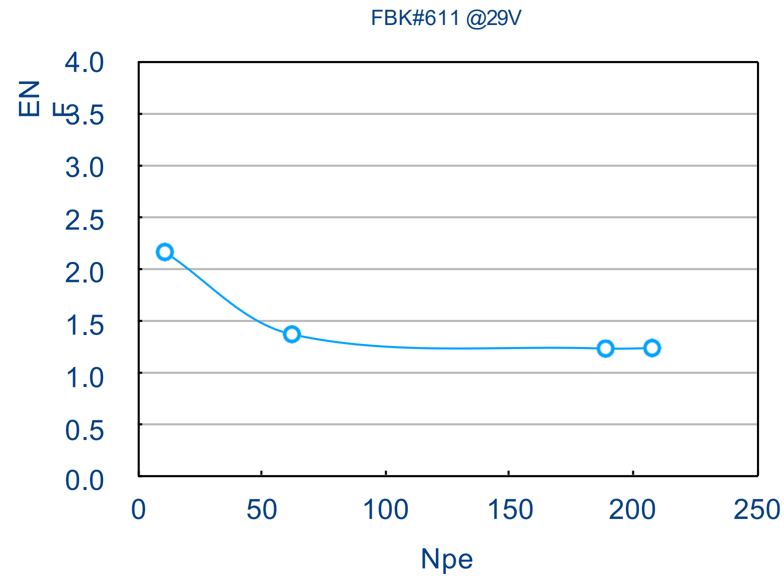
FBK SiPM I-V Curves





Excess Noise Factor of FBK #611



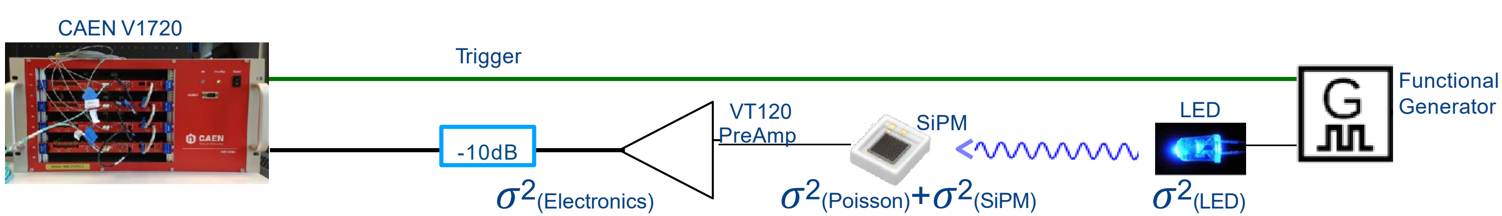


$$\sigma^2_{(observed)} = \sigma^2_{(Poisson)} + \sigma^2_{(SiPM)} + \sigma^2_{(Electronics)} + \sigma^2_{(LED)}$$

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

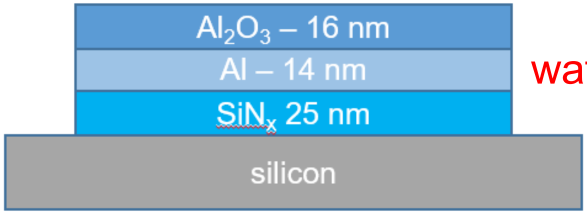
$$= N_{pe\,(Poisson)} \times (1 + \sigma^2_{(pe)} + \sigma^2_{(Pedstal)}/N_{pe} + \sigma^2_{(LED)}/N_{pe})$$

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



J. Oyang

FBK SiPM with three layer filter

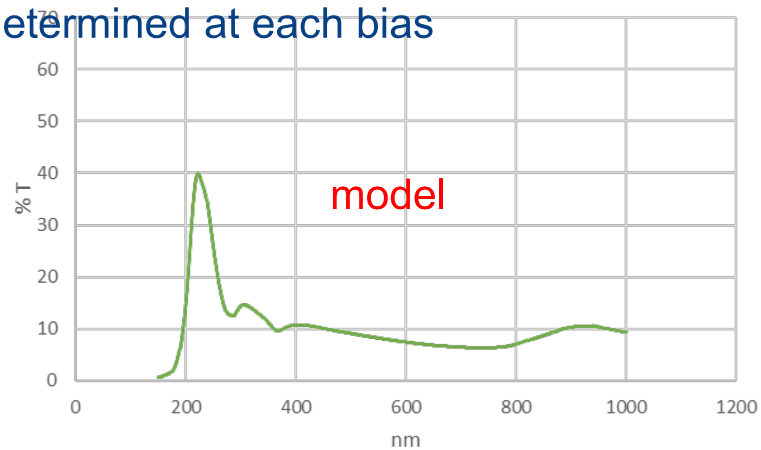


wafer 11

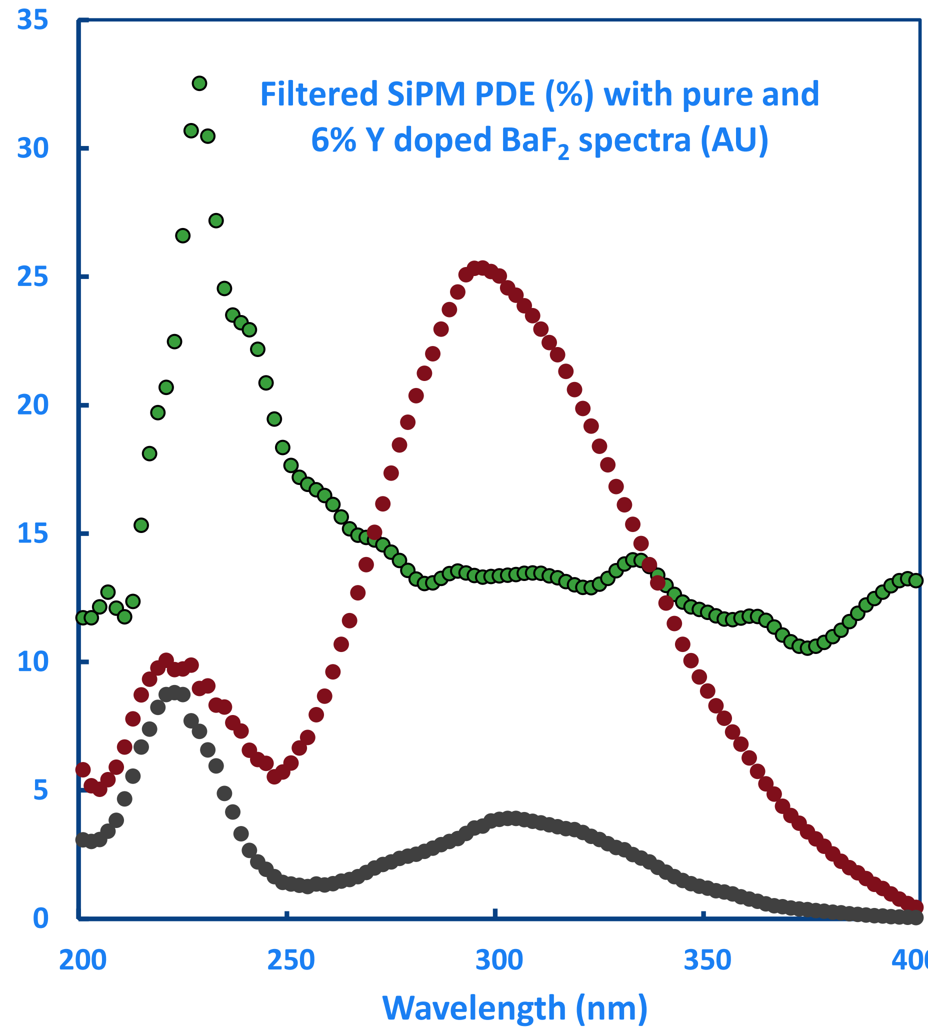
PDE scanned *vs.* wavelength at several bias voltages, with gain measured

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

Excess noise factor determined at each bias

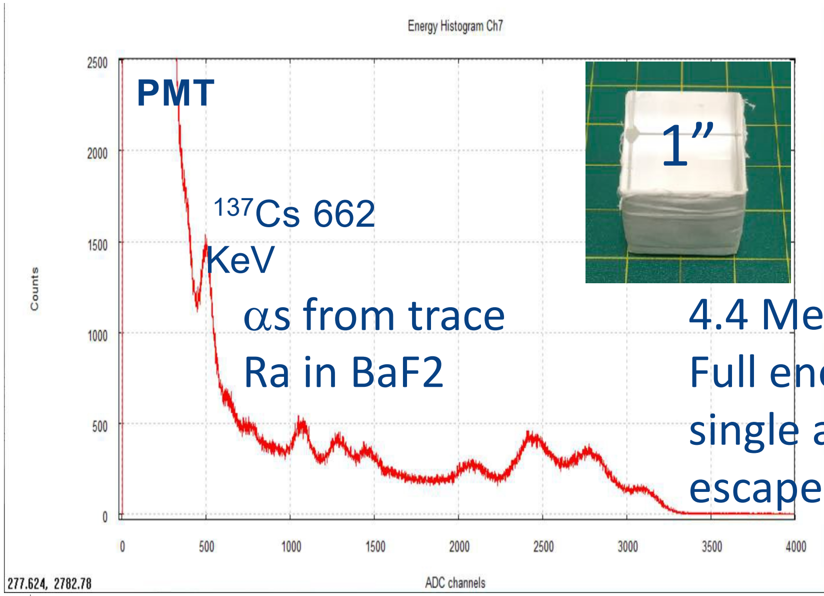


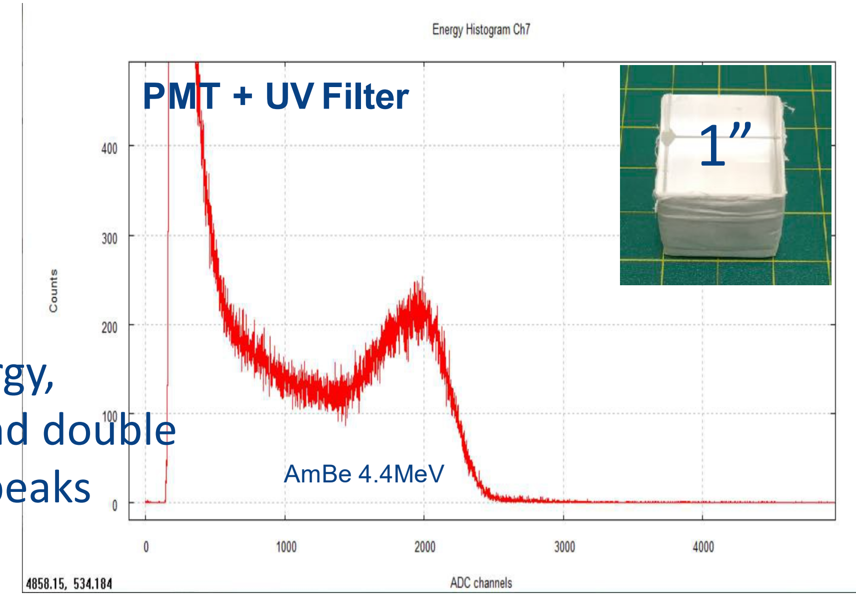
measurement

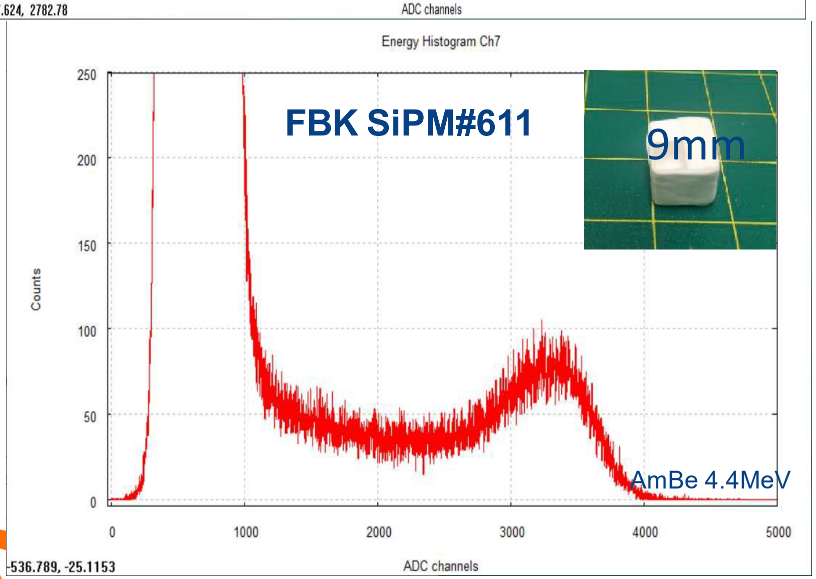


L. Zhang, J. Oyang

BaF_2 + AmBe Read out by PMT and FBK#611



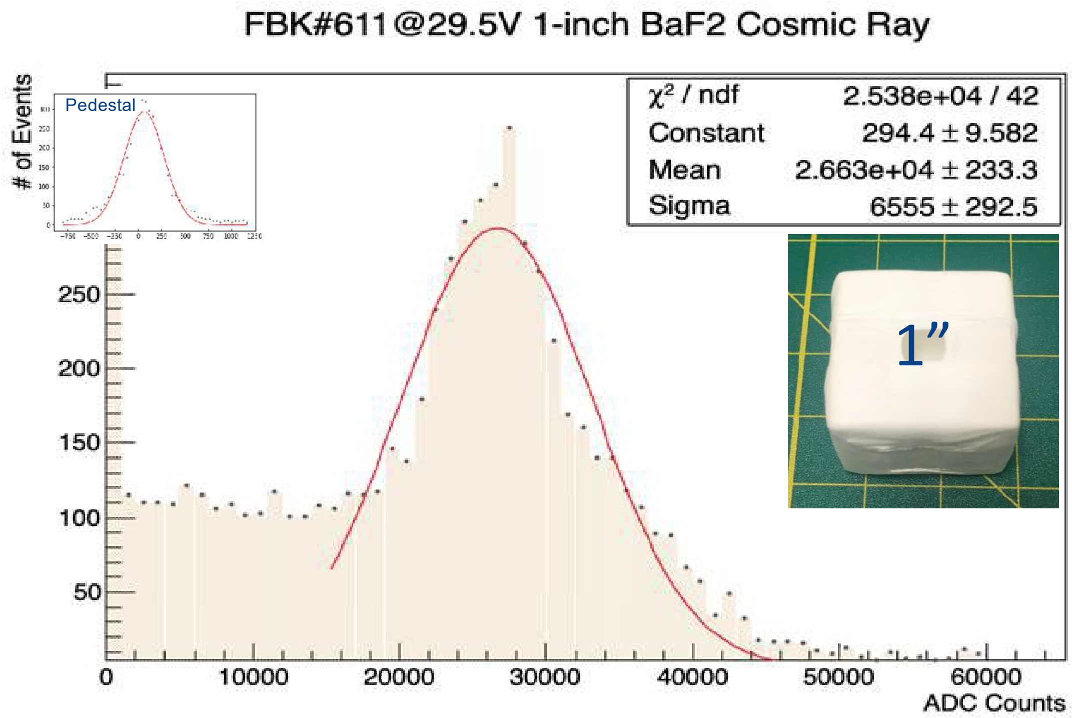




- An AmBe neutron source emits copious 4.4 MeV gammas
- FBK SiPM #611 operated at 29.5V
- BaF_2 dimension 9 x 9 x 9 mm, wrapped with teflon with an opening of 6x6 mm
- 3400 (adc)/29.1(pe/adc) = 117 pe
- 117 pe / 4.4 MeV = 27 pe/MeV

J. Oyang

FBK #611 BaF_2 Cosmic Ray Spectrum

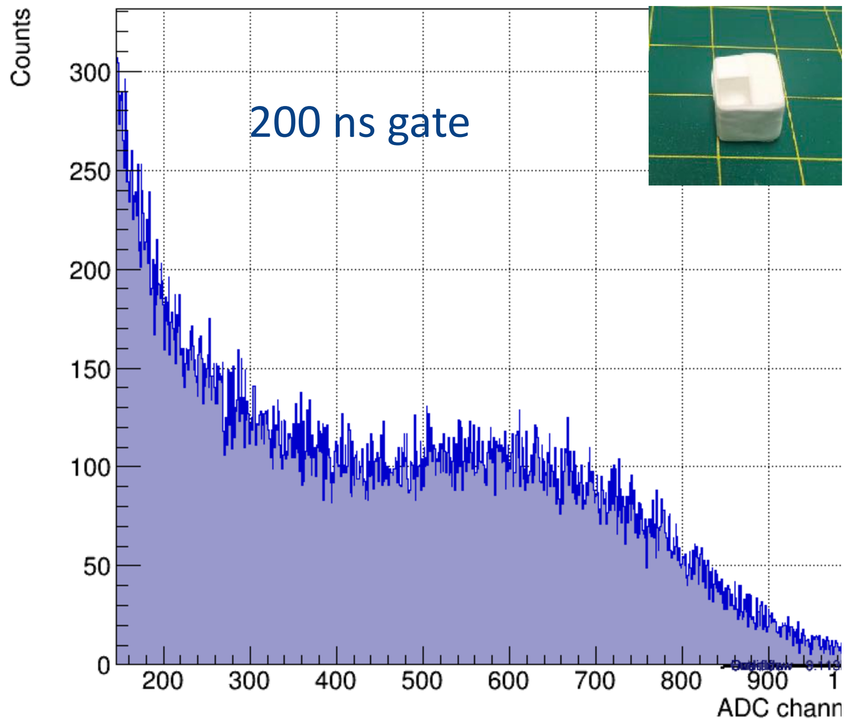


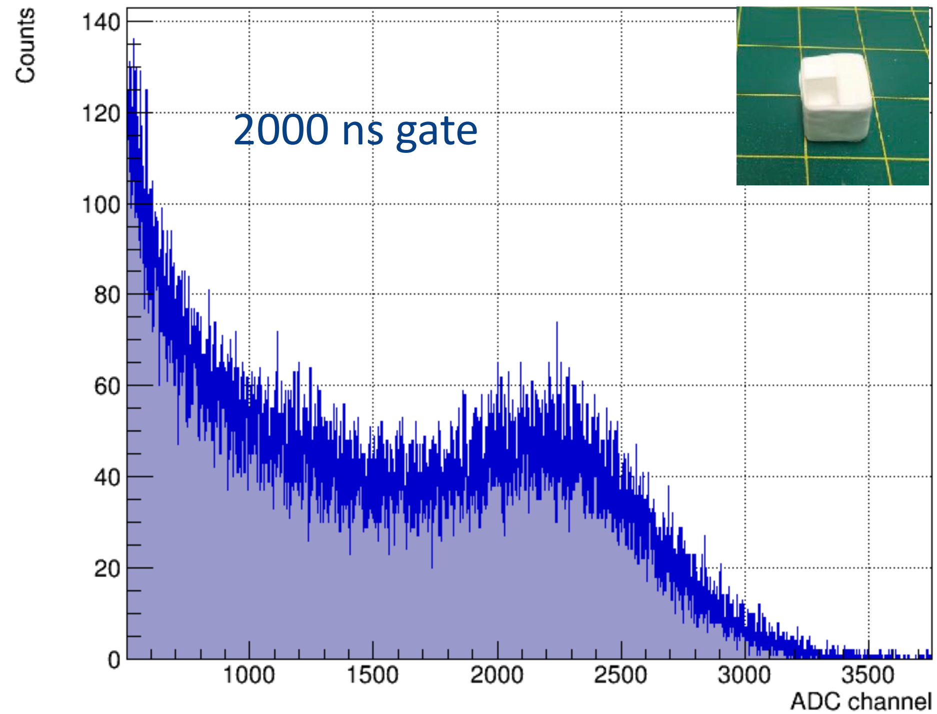
- FBK SiPM #611, dimension 6x6 mm, operated at 29.5V
- BaF_2 dimension 1” x 1” x 1”, wrapped with teflon with an opening of 6x6 (mm)
- Cosmic ray deposits 6.374 MeV/cm * 2.54 cm = 16.2 MeV
- (26631 - 68) adc / 148 pe/adc = 180 pe
- 180 pe / 16.2 MeV = 11 pe/MeV   With 2x3 array, expect 60-70 pe/MeV

J. Oyang

SiPM 611 BaF_2 with AmBe source (4.4 MeV)

9 mm BaF_2



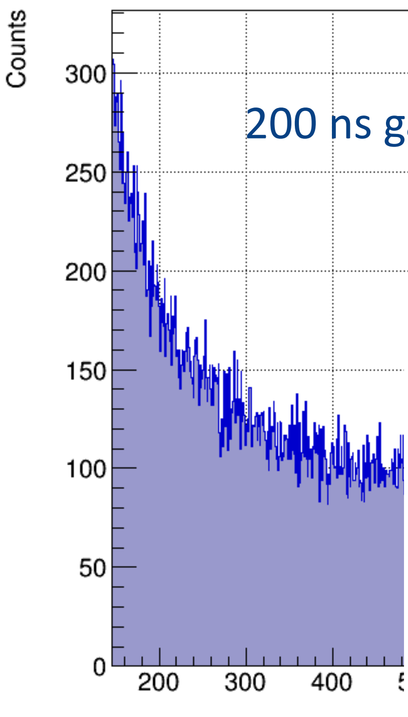


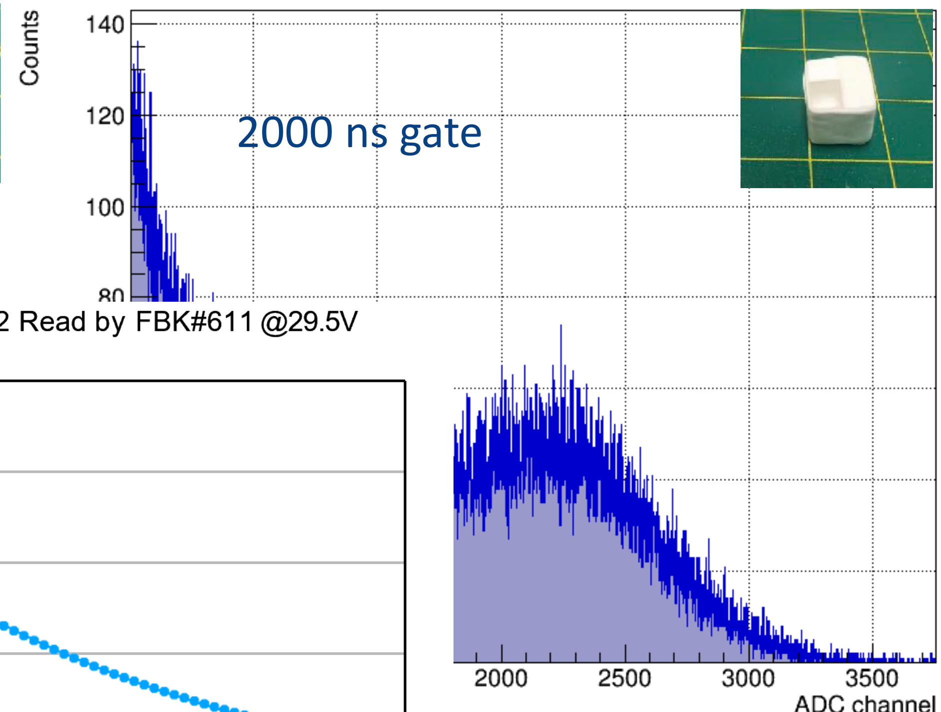
Use of 200 and 2000 ns gates allows extraction of ratio of slow to fast scintillation components seen by filtered SiPM: ~4

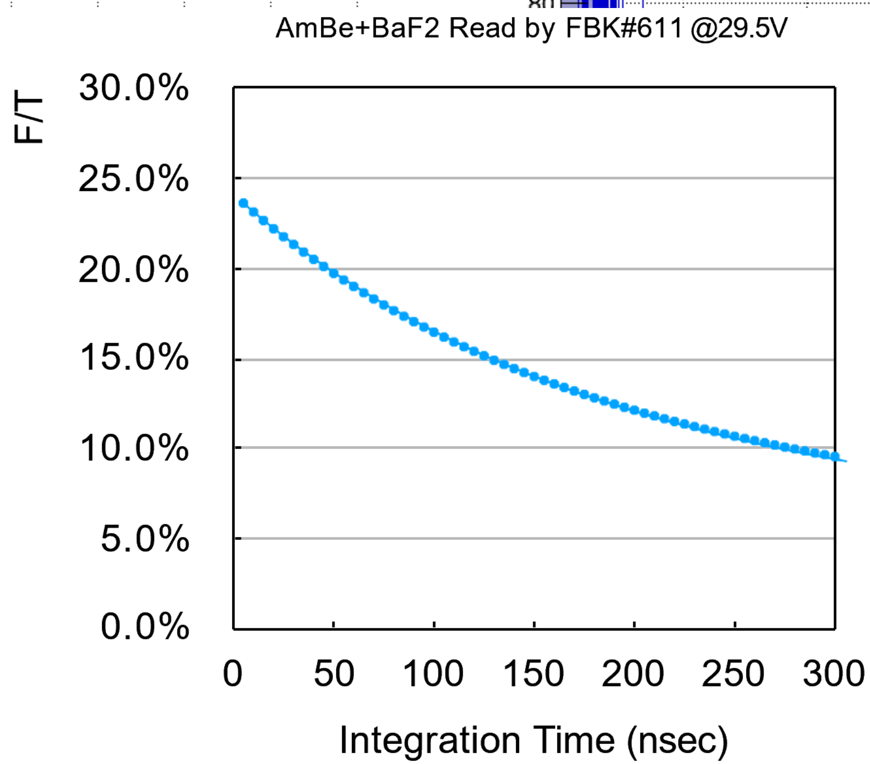
J. Oyang

SiPM 611 BaF_2 with AmBe source (4.4 MeV)

9 mm BaF_2



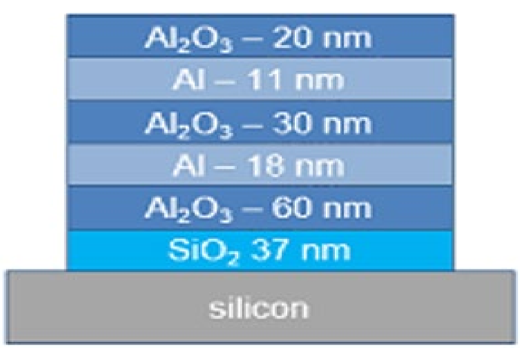


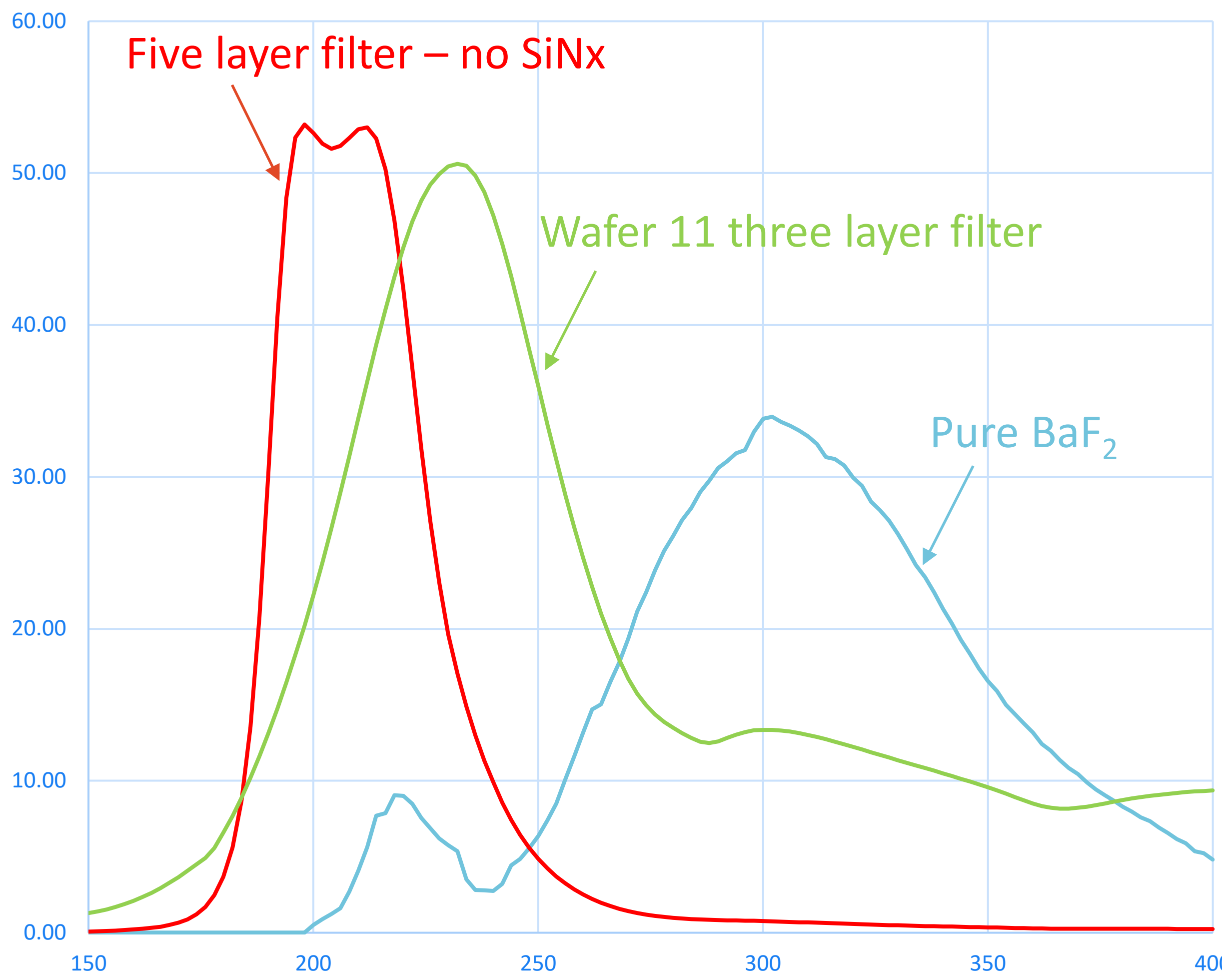


Use of 20(... atio of slow to fast
scintillatio

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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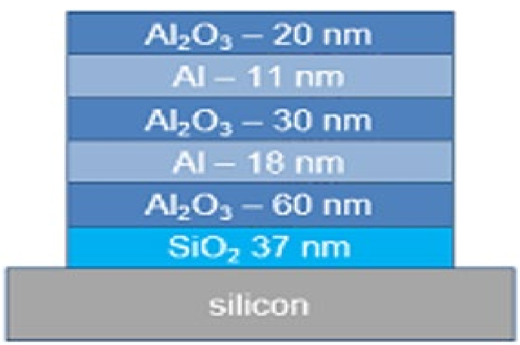

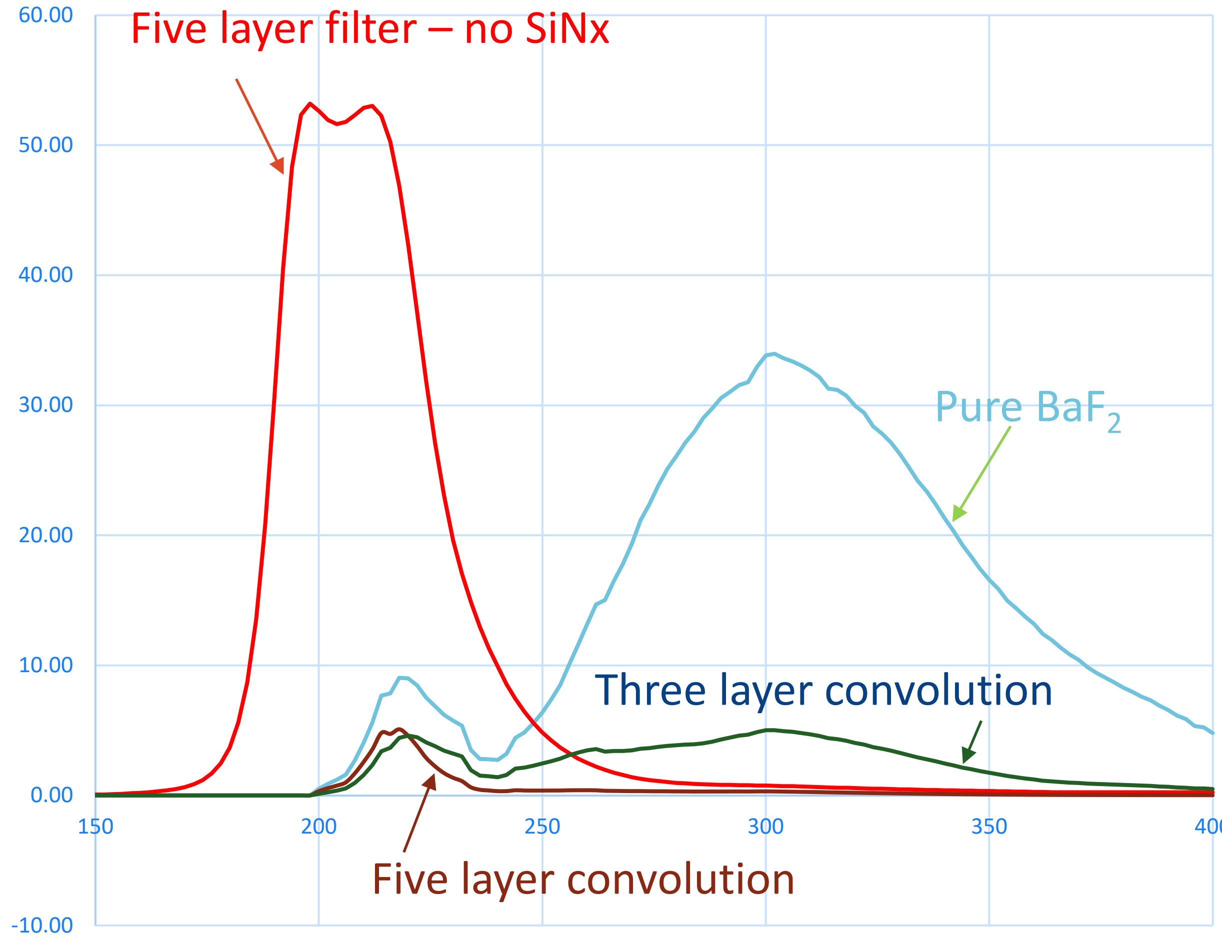

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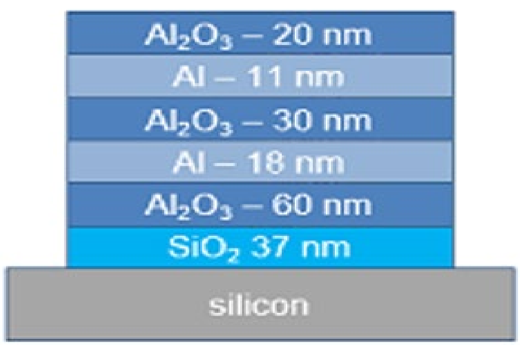
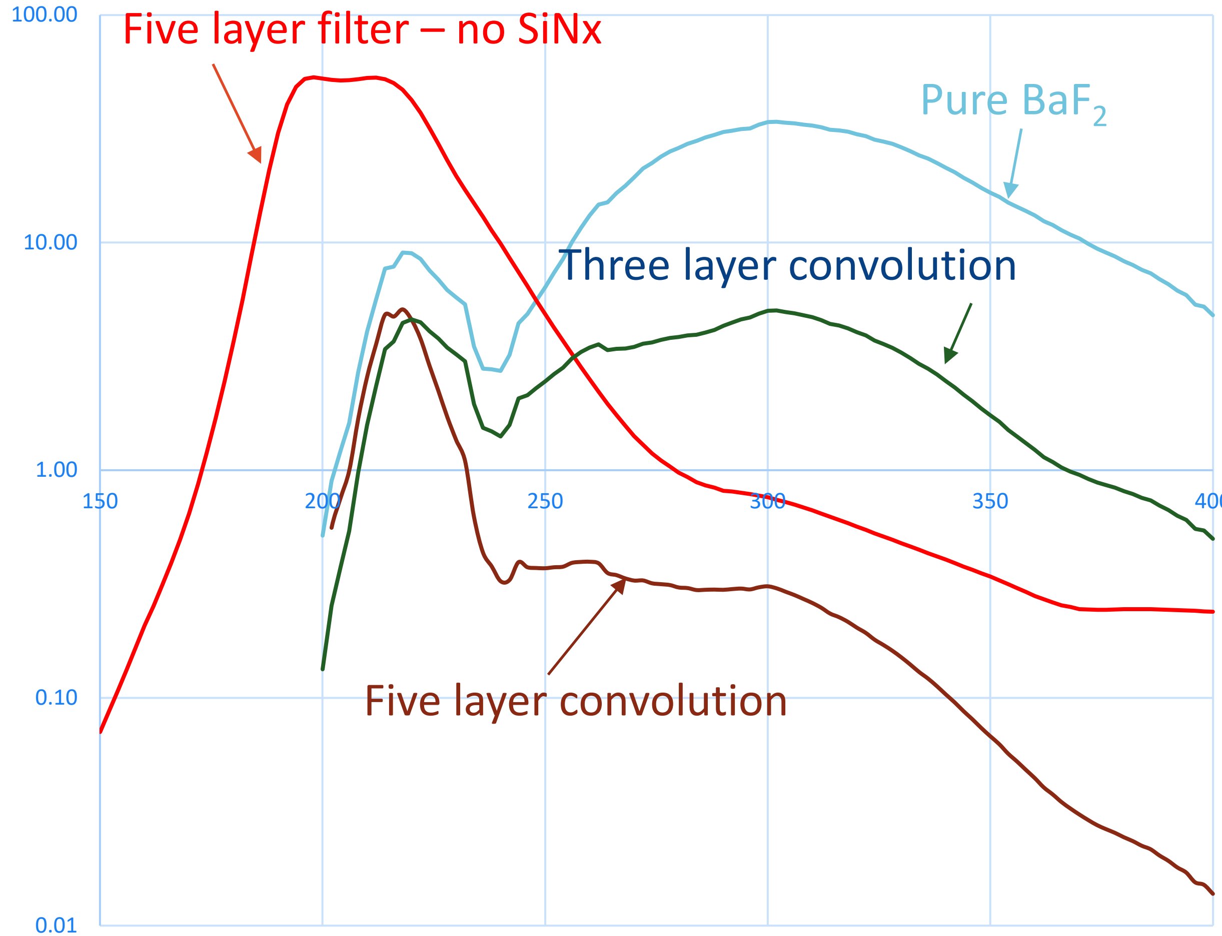
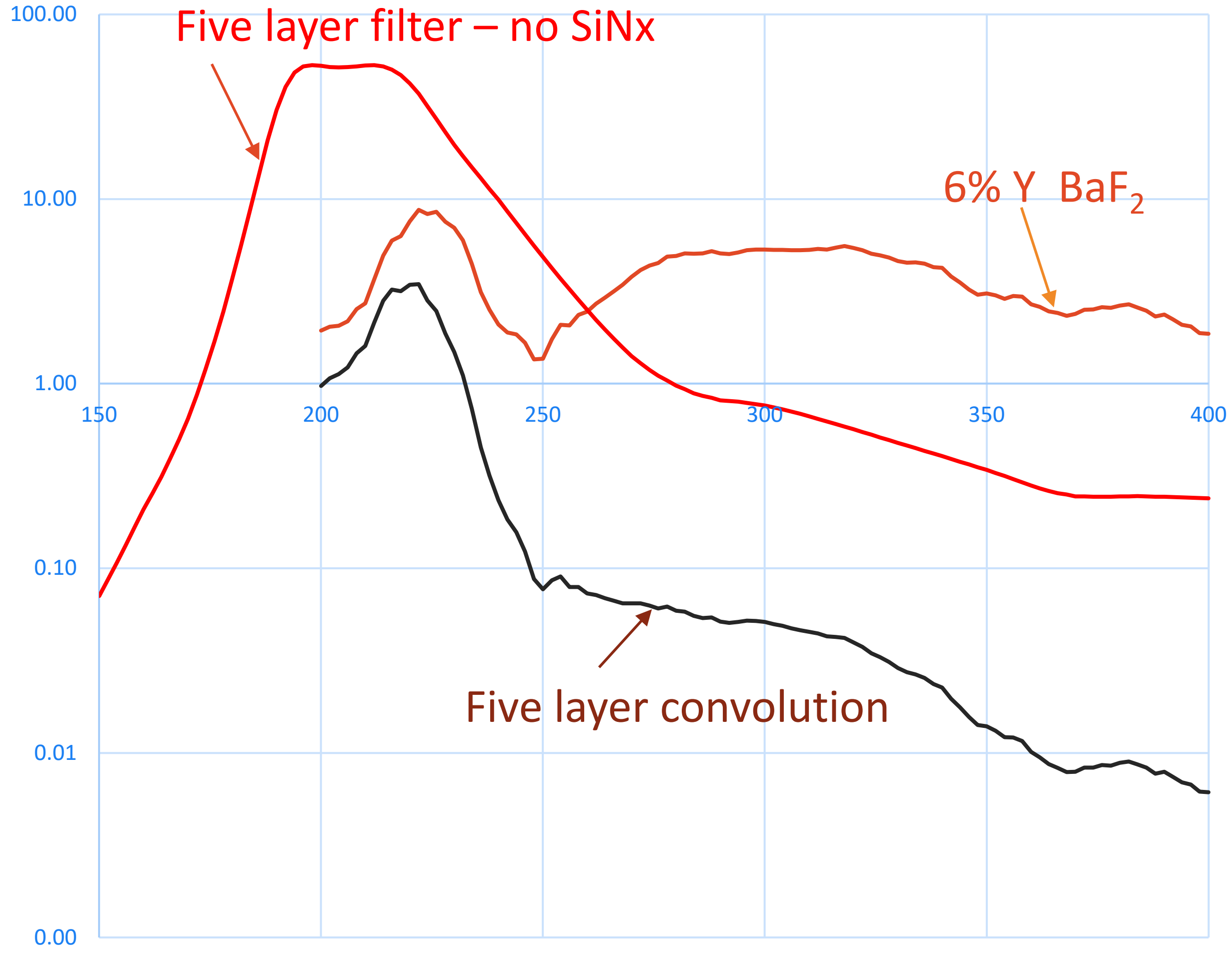




Further improvement of fast/slow performance

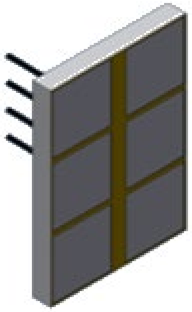
- Combining
  - 6% Y-doped BaF_2 and
  - SiPM with a five layer filter

  provides further improvement in the ratio of fast to slow scintillation components
- This performance should be adequate for the Mu2e-II calorimeter



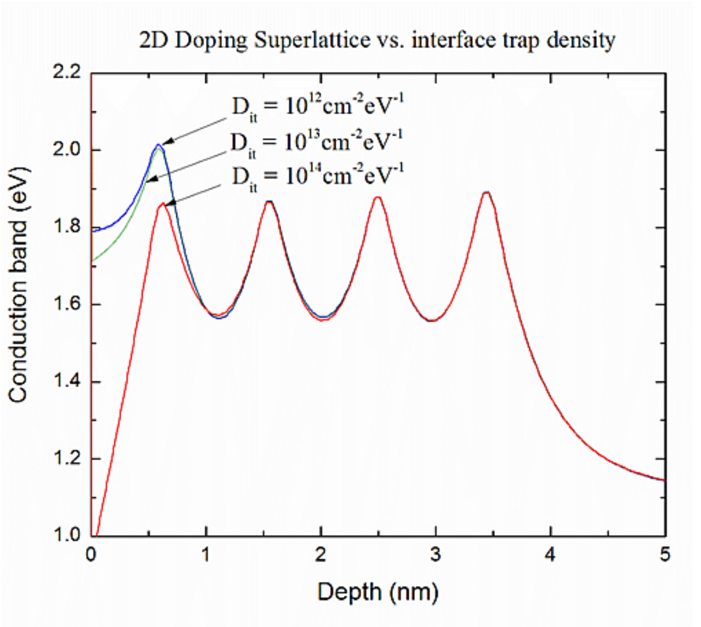
Current status and plans

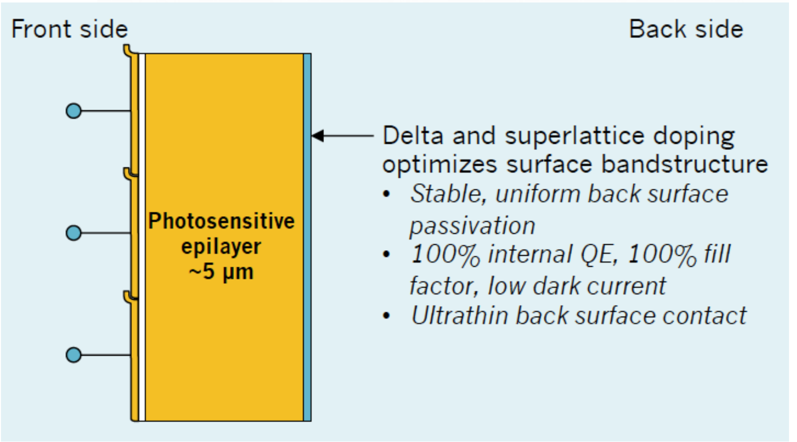
- Next steps
  - Spectra with Y-doped BaF_2 crystals, slow fast scintillation yield
  - Use 3 x 2 chip array of 6x6mm chips in series/parallel configuration with larger crystals – we have just received samples
  - Radiation hardness studies with γs and neutrons
  - MTF burn-in studies
  - Fab more sophisticated five-layer filters on remaining wafers – this is getting underway as JPL reopens
  - Produce delta-doped, back-illuminated versions that will have improved QE and timing characteristics



Superlattice structures

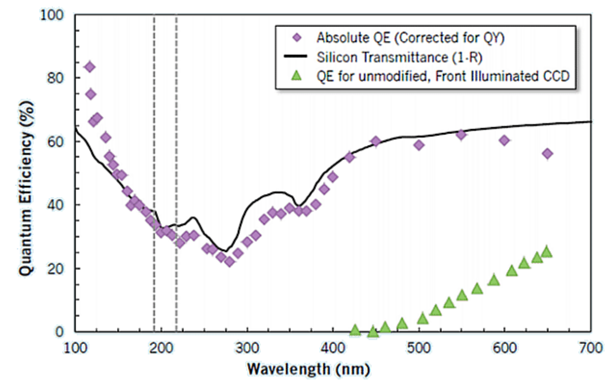
- JPL has developed superlattice structures that provide enhanced quantum efficiency and improved time response for photosensors
  - Delta-doping and superlattices have been successfully employed for many years to enhance the UV performance of CCDs and APDs used in UV astronomy in satellites and balloons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



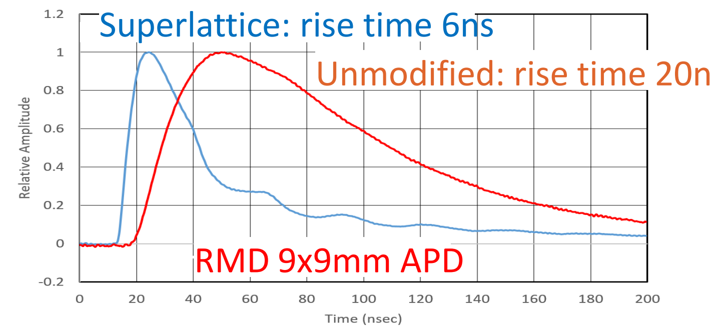


Superlattice MBE performance

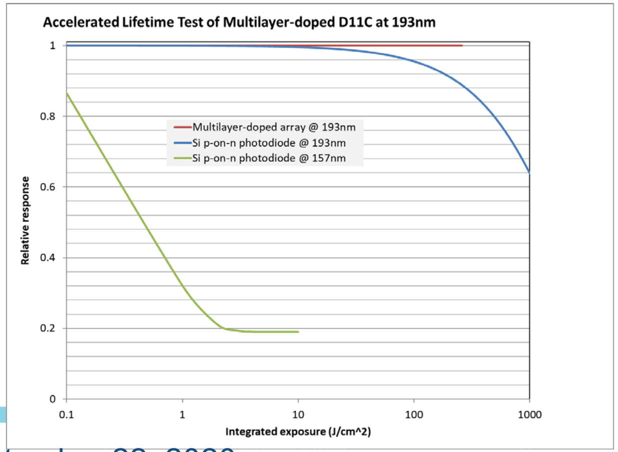
- Recombination of photoelectrons is suppressed by quantum exclusion, resulting in close to 100% internal QE
  - Quantum efficiency in the 200-300 nm region approaches the silicon transmittance (1-R) limit



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



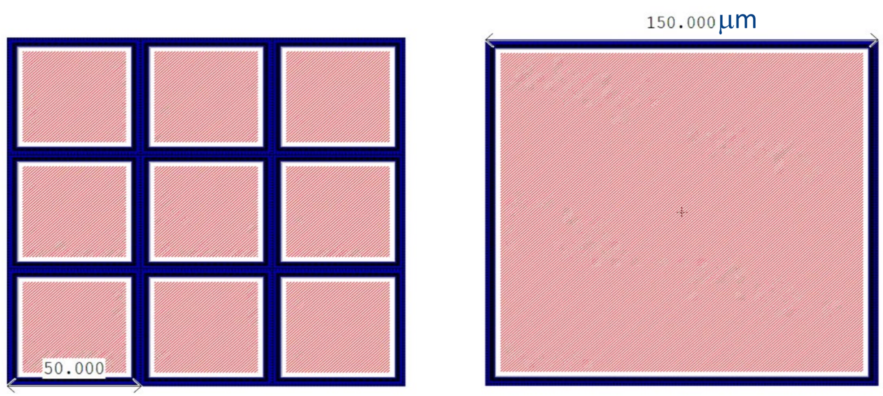
- The superlattice structure provides stability under intense UV illumination
  - Relevant regime for Mu2e-II is ~ 1-10 J/cm^2



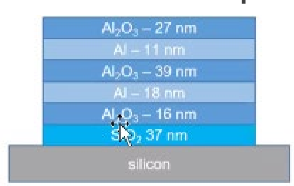
U. Arp *et al.,* J. Elect. Spect. and Related Phenomena, **144**, 1039 (2005)

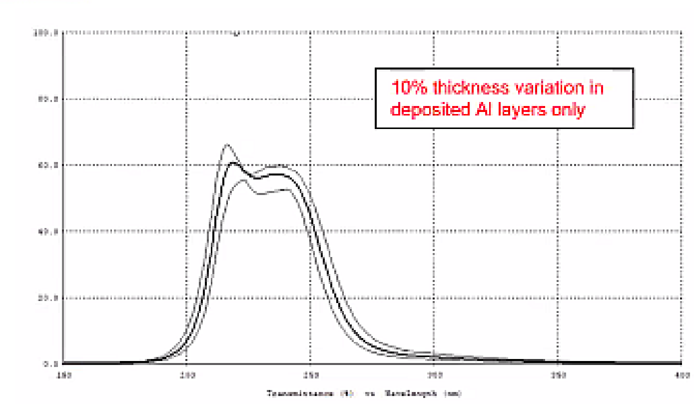
Next steps

1. Incorporation of MBE layer
   - In order to decouple the details of fabricating surface structures from the avalanche structures, this will first be done on a photodiode
   - MBE will be applied to diode structures with SiPM-like layouts of different area, in order to evaluate leakage current from trenches and the MBE layers



   - More complex filters will be incorporated

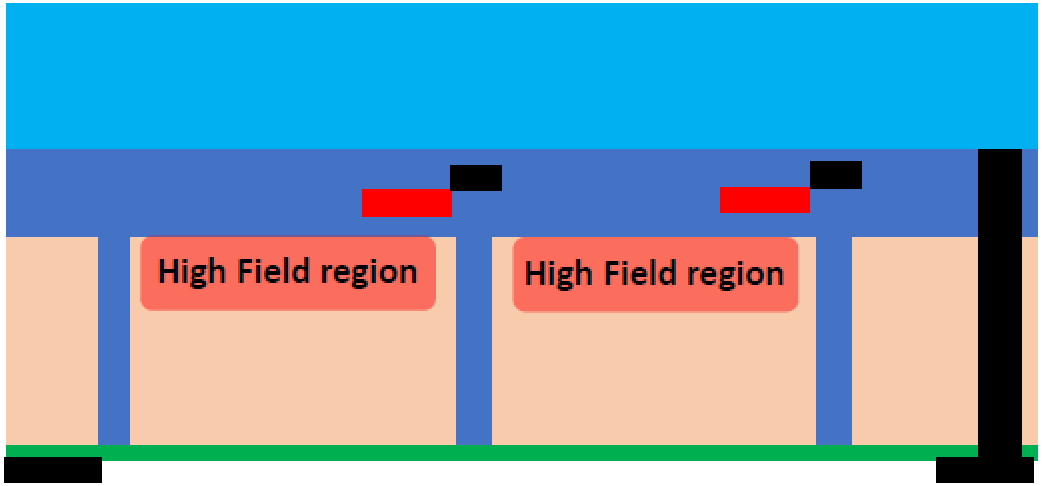




   - Wafers for this series have been ordered

Next steps – the ultimate goal

2. Back Side SiPM with MBE
   - Decouples illumination/collection region and high field avalanche region
   - Provides a higher fill factor
   - MBE on back side – more options for filter design
   - Requires wafer thinning and bonding



   - Will incorporate what we learn from MBE on 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 would be useful 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