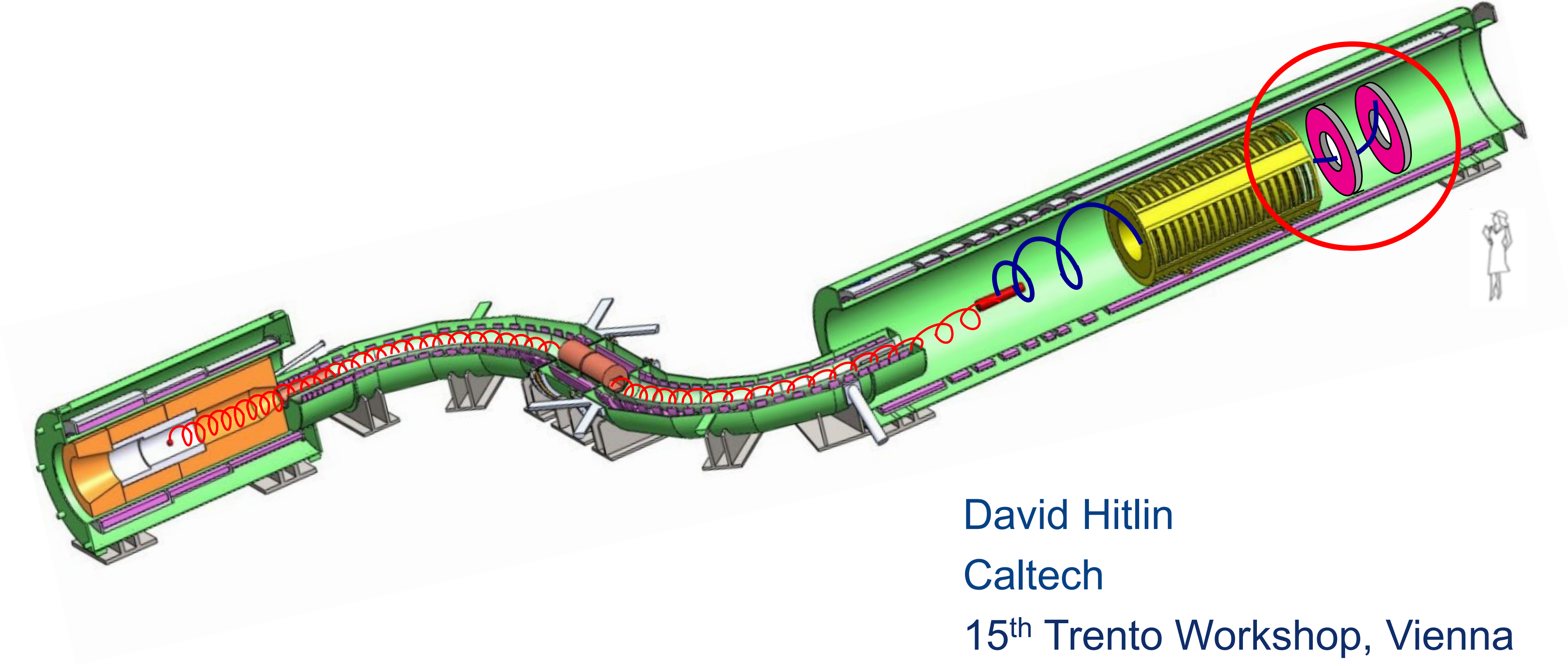
Progress on a photosensor for the readout of the fast scintillation light component of BaF_2

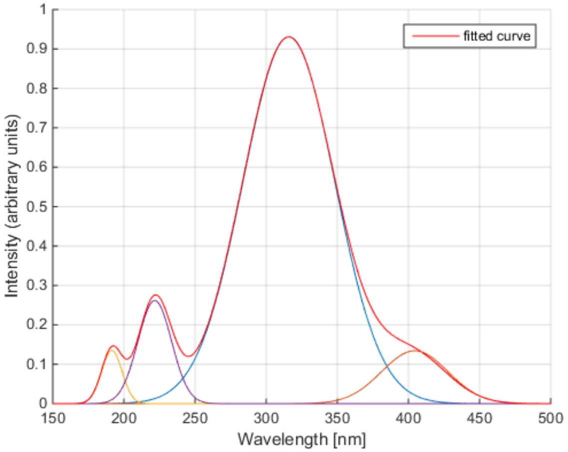


David Hitlin

Caltech

15th Trento Workshop, Vienna
February 19, 2020

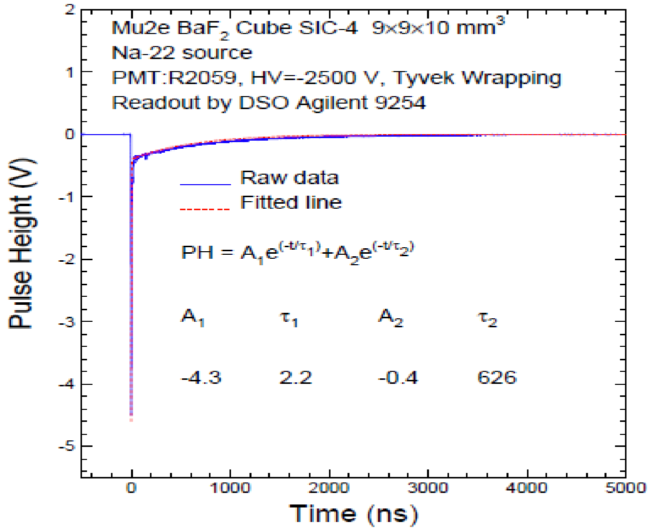
Photosensor options for BaF_2 readout



- BaF_2 has long been identified as an excellent choice for a fast, high rate, radiation-hard calorimeter or PET detector, 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 ($\tau < 1$ ns) at 195 and 220 nm and two slow components ($\tau = 630$ ns) at 320 and 400 nm
- Viable approaches:
  1. Directly suppress the slow scintillation component
     - Suppression of the BaF_2 slow component by Y doping, as developed by Zhu *et al.*,: a major advance, although R&D remains
  2. Interpose an external filter
     - TAPS at ELSA (Mainz) – filter+PMT
  3. Use a photosensor that is sensitive only to the fast component
     - SiPM development by Caltech/FBK/JPL
     - [Solar-blind MCP or LAAPD]
  4. Combine 1 and 2 or 1 and 3

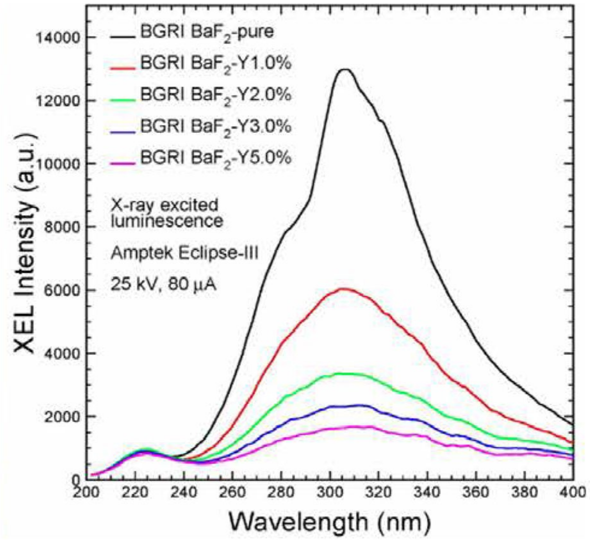
Pure and doped BaF_2

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

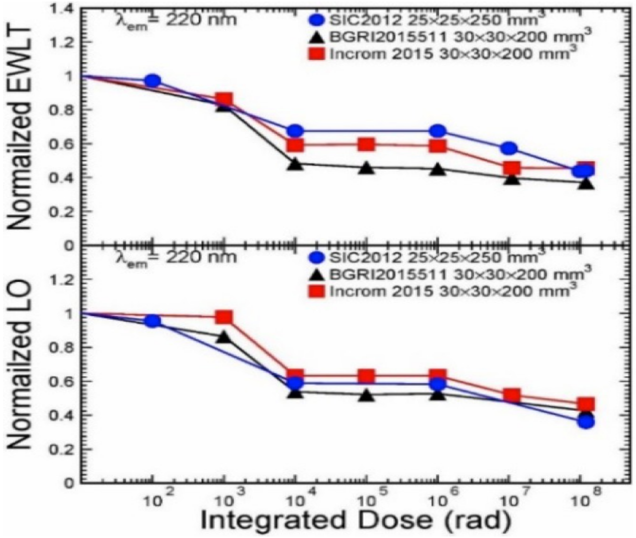


R.-Y. Zhu.
CPAD 2019

Y doping can suppress slow scintillation component



Radiation hardness



Photosensor options for pure or Y-doped BaF_2

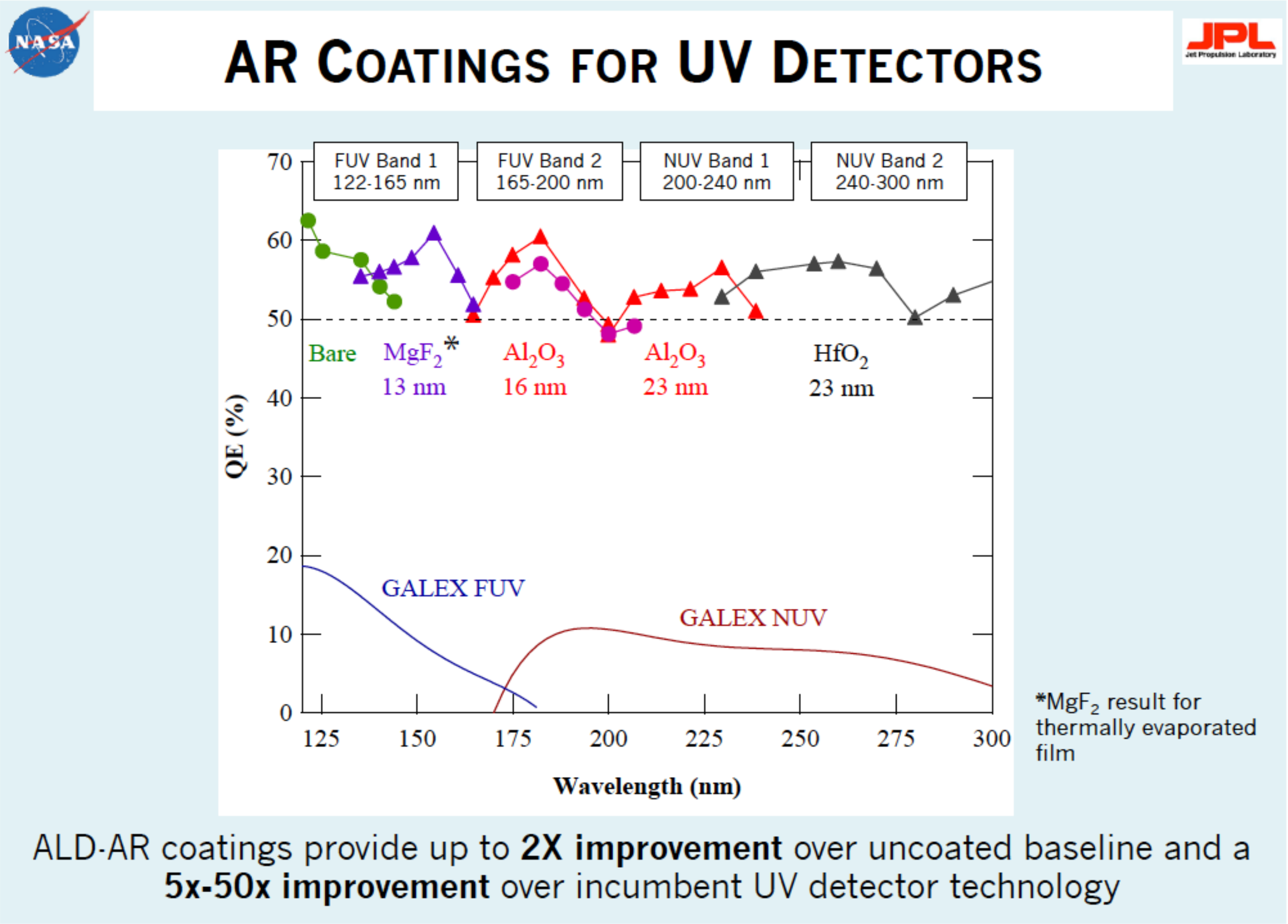
- What is required of an appropriate photosensor?
  - Spectral sensitivity in the 200 nm region for best energy and time resolution
  - Fast/slow component discrimination for high rate capability
  - Best feasible rise/fall time characteristics to fully capitalize on the fast component native time resolution and rate capability
  - Radiation hardness (photons/neutrons)
- Photosensor candidates
  - Large area SiPMs developed for the MEG upgrade, DUNE, …having ~25% PDE at 220nm (these already exist – *e.g.*, Hamamatsu, FBK,,), but no fast/slow component discrimination
  - Large area delta-doped APDs with an integrated filter, having ~50% PDE at 220nm and strong suppression at 320nm developed at Caltech/JPL/RMD
    - These have large dark current and more noise than standard RMD devices, but can be run at reduced temperatures
  - Large area SiPMs with an integrated filter and potentially improved time response are currently under development at Caltech/JPL/FBK
  - Affordable rad hard, solar blind MCPs, LAPPDs

CIT/FBK/JPL SiPM - a phased approach

- We have adopted a phased development approach
  1. Build a three layer ALD filter on existing 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 determination
  - PDE as a function of wavelength, demonstrating filter performance
  - Radioactive decay spectra with small BaF_2 crystals

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

ALD antireflection filters improve QE



AR COATINGS FOR UV DETECTORS

*MgF_2 result for thermally evaporated film

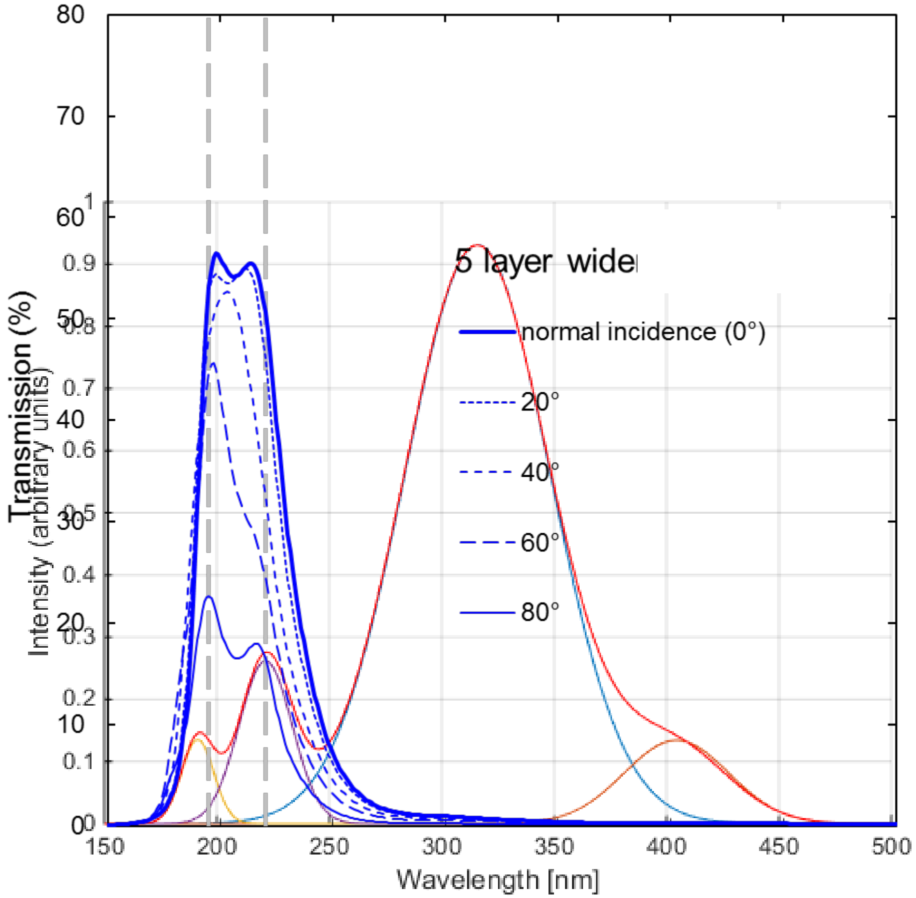
ALD-AR coatings provide up to **2X improvement** over uncoated baseline and a **5x-50x improvement** over incumbent UV detector technology

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

ALD bandpass interference filters

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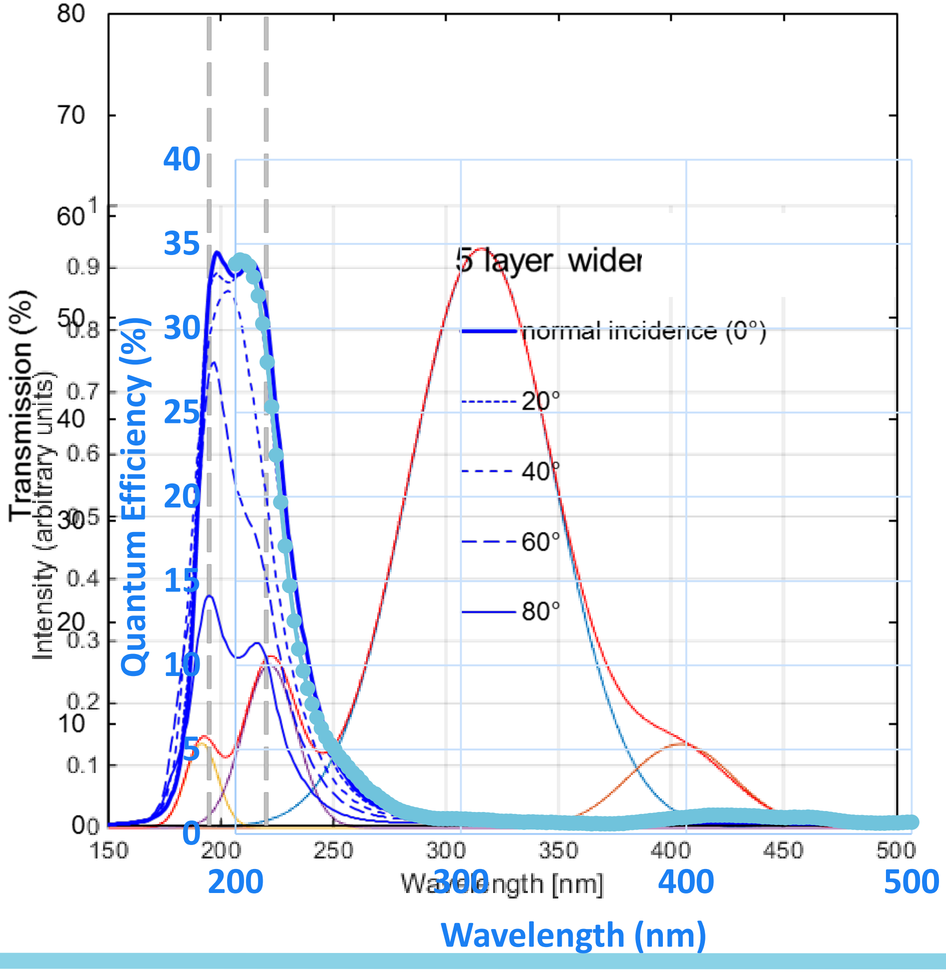
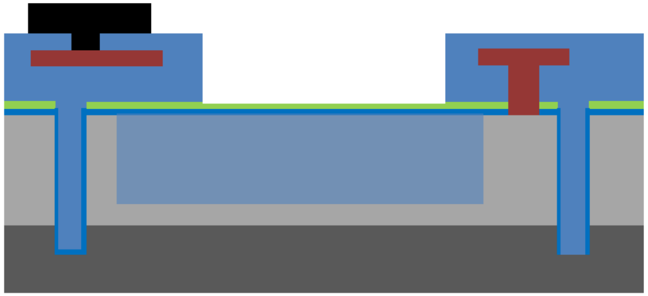


Measurement scaled using a model to QE at nominal gain/bias

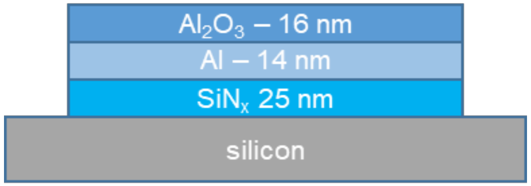
SiPM fabrication and test



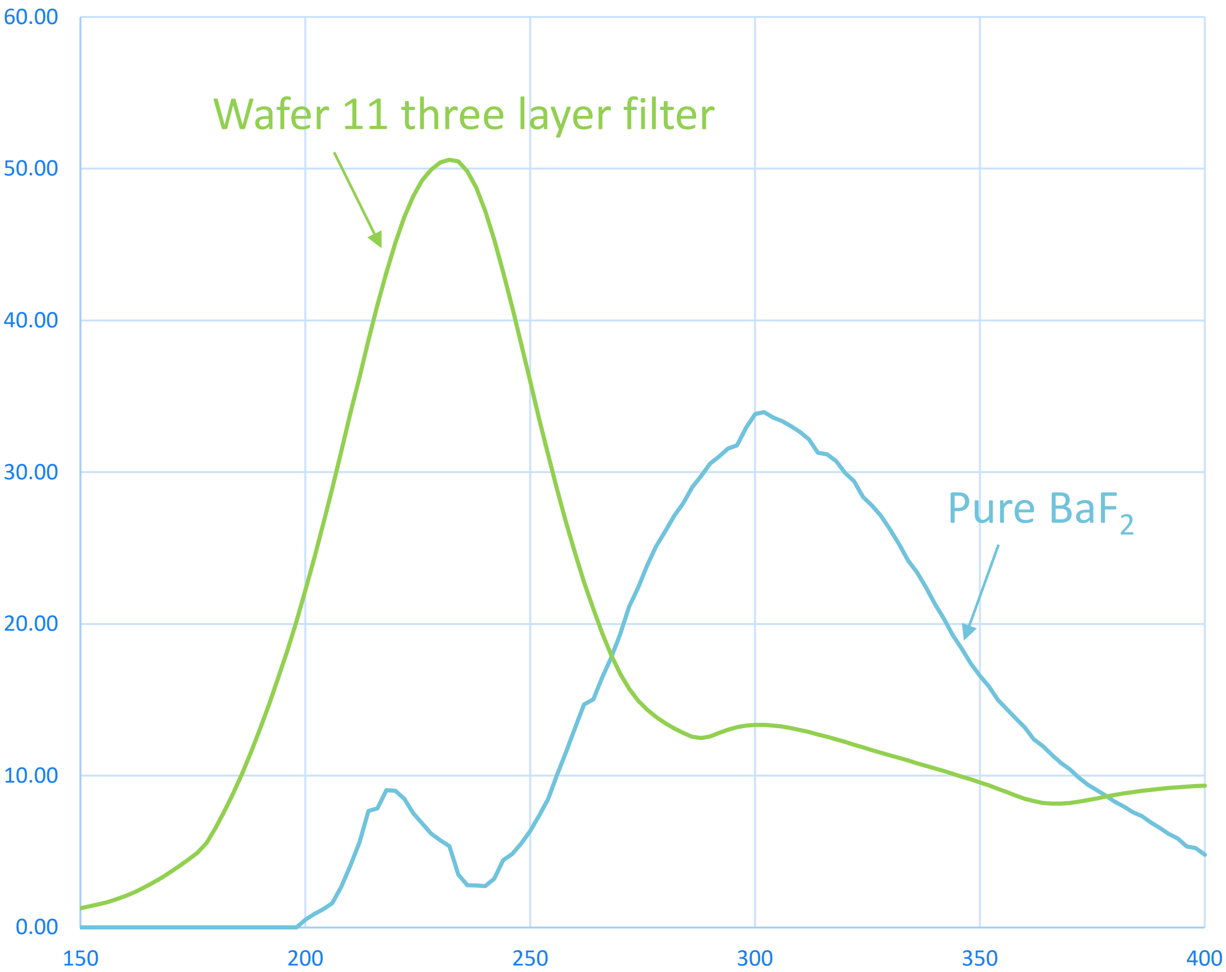
- FBK fabricates wafers based on current NUV designs, with various modifications, including guard ring structures
- FBK thins SINx passivation layer
- ALD filters are deposited at JPL
- The wafers are returned to FBK for probing and dicing into chips
- 6x6mm devices with three layer filters have been fabricated in this way and tested at Caltech
  - Filter performance and PDE measurement with spectrophotometer down to 200nm
  - Characterization of excess noise performance
  - Radioactive decay spectra with pure BaF_2 crystals, slow fast scintillation yield

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


Al_2O_3 – 16 nm
Al – 14 nm
SiN_x 25 nm
silicon

Wafer 11



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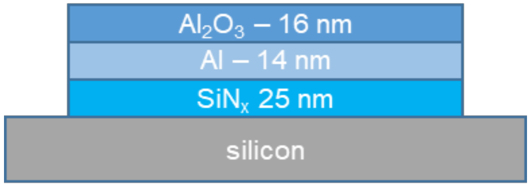
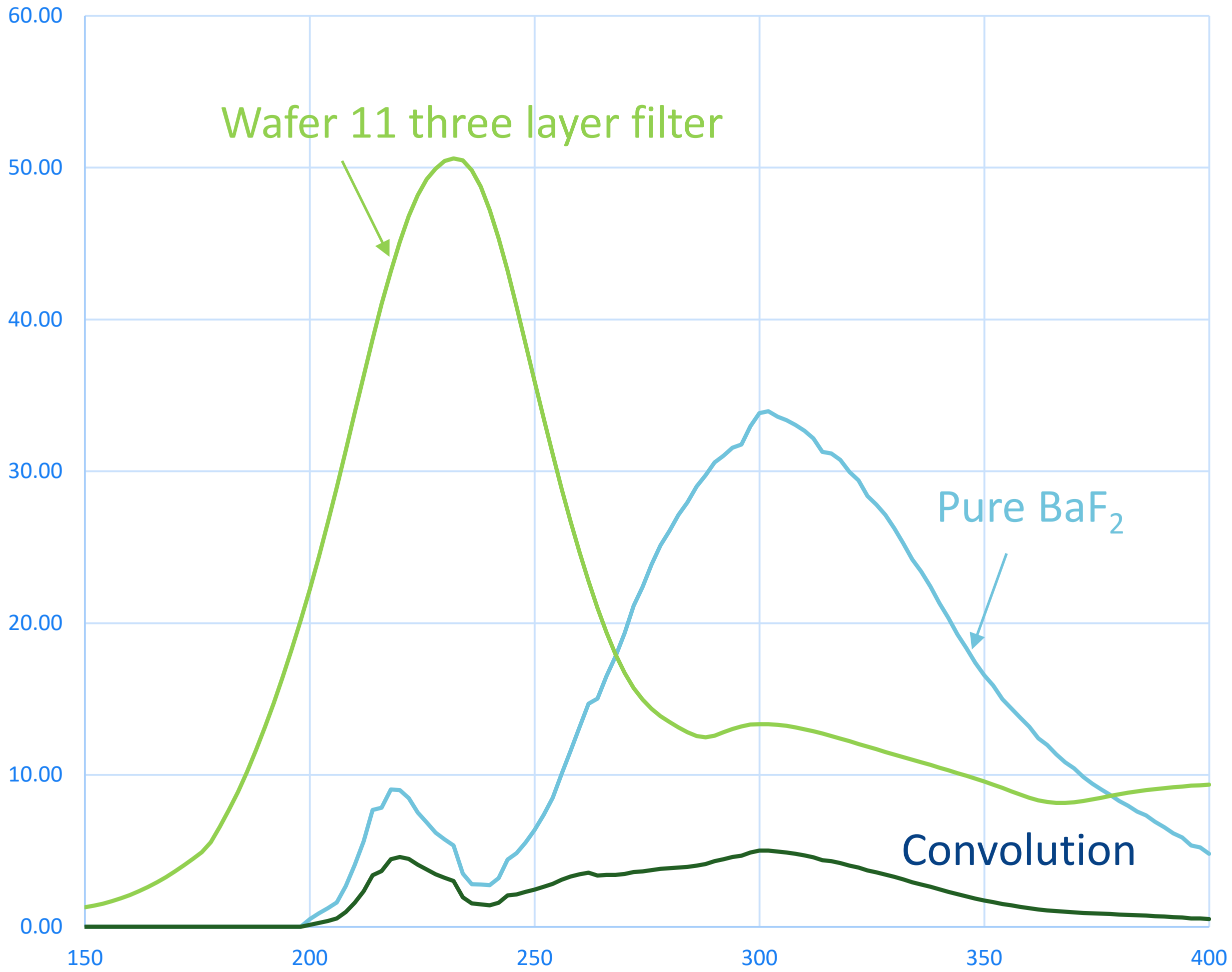
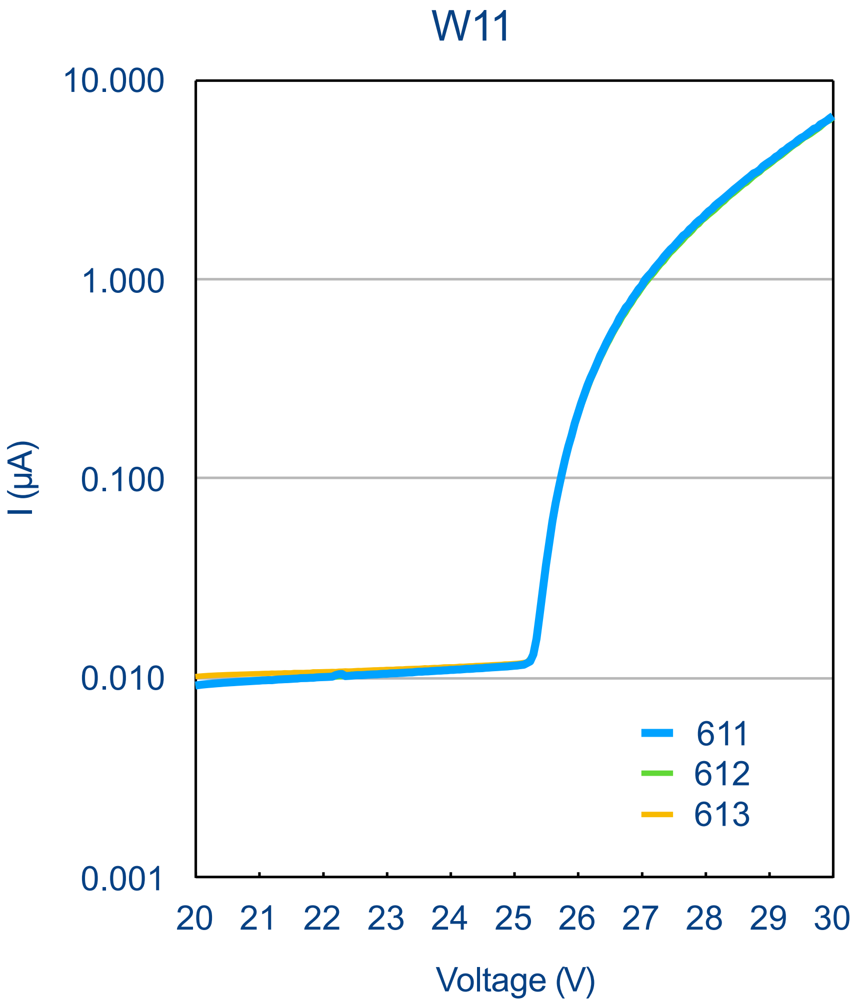
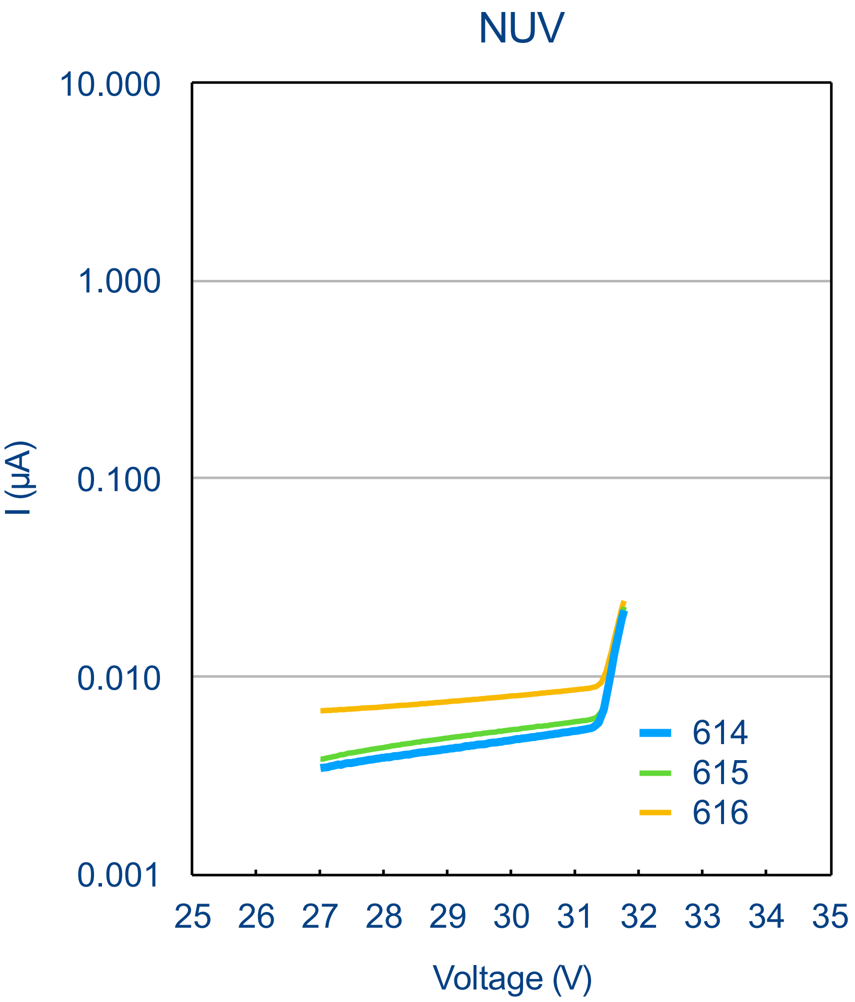




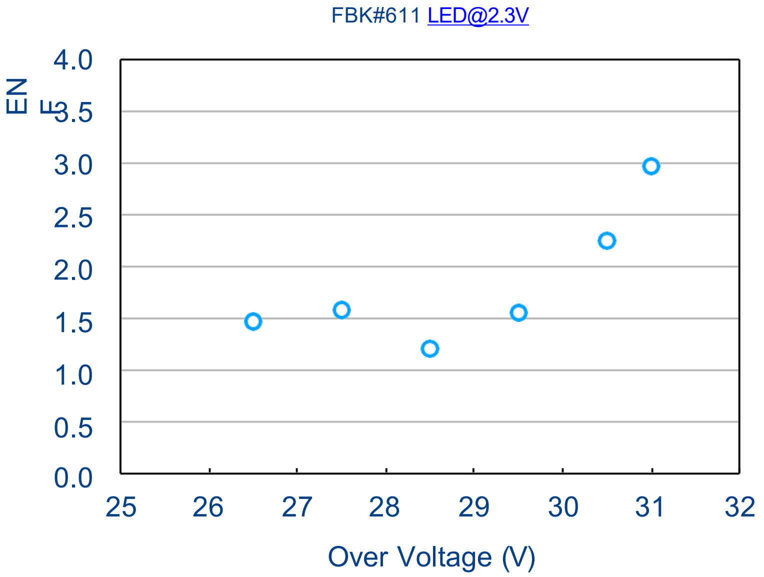
Wafer 11

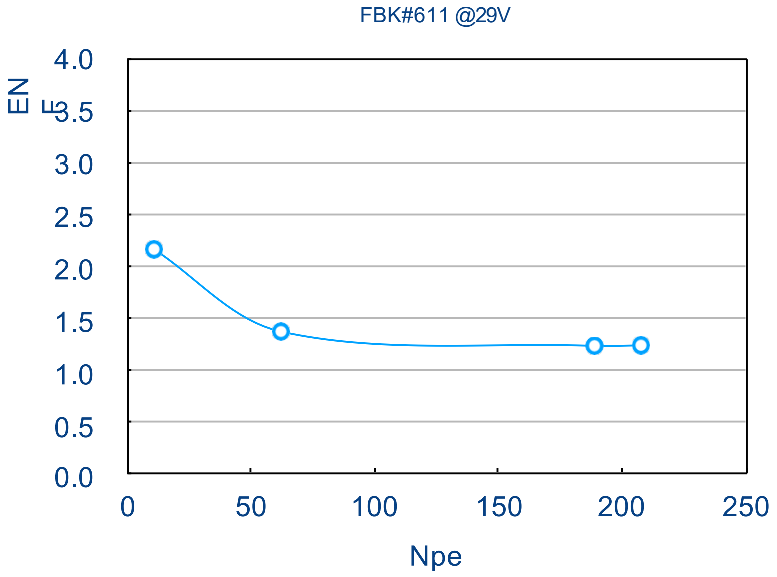
FBK SiPM I-V Curves





Excess Noise Factor of FBK #611



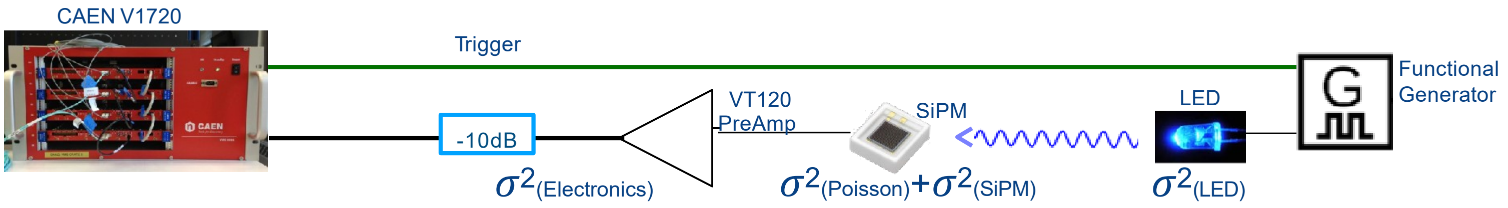


$$\sigma^2_{(observed)} = \sigma^2_{(Poisson)} + \sigma^2_{(SiPM)} + \sigma^2_{(Electronics)} + \sigma^2_{(LED)}$$

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

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

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



$\sigma^2_{(Electronics)}$

$\sigma^2_{(Poisson)}+\sigma^2_{(SiPM)}$

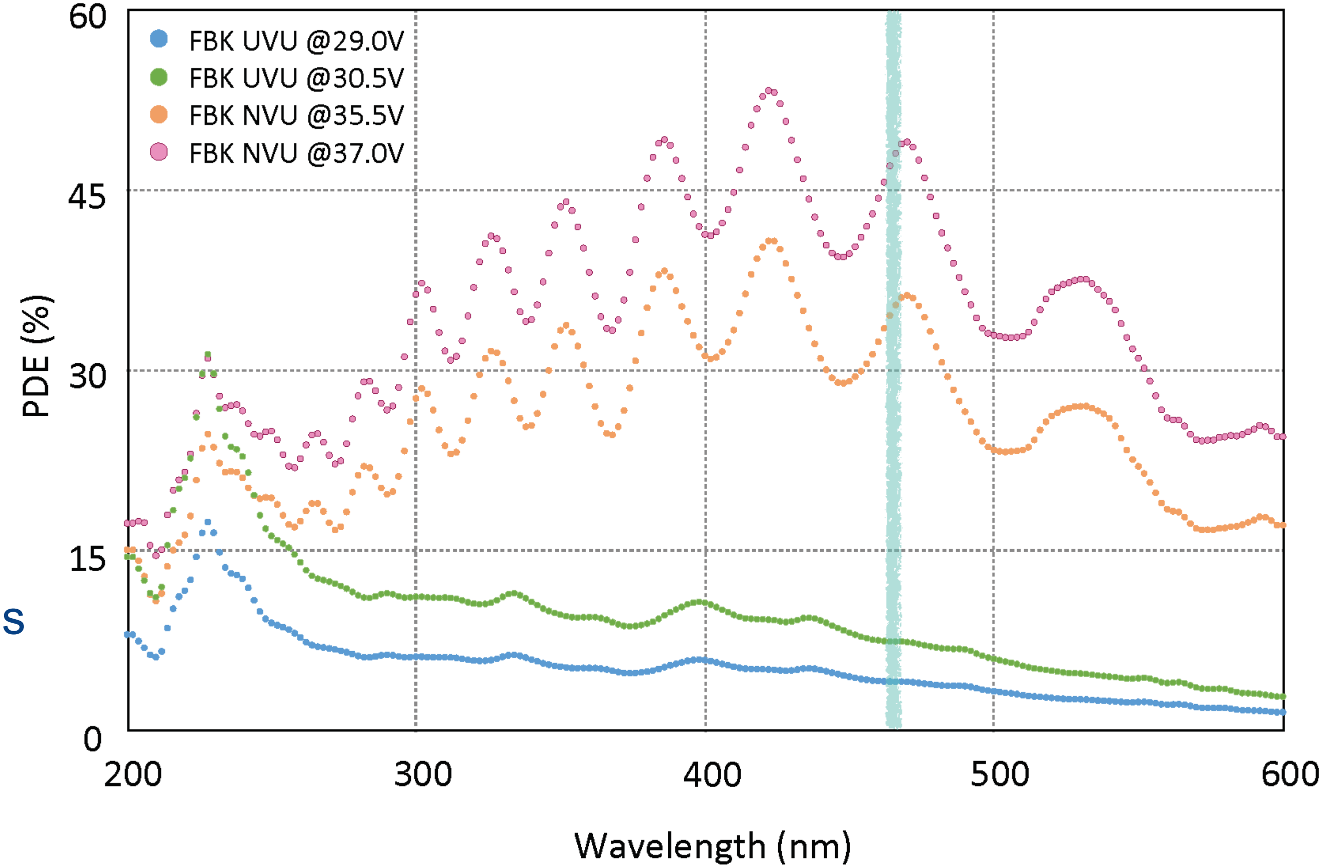
$\sigma^2_{(LED)}$

Measured PDE of FBK SiPMs

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

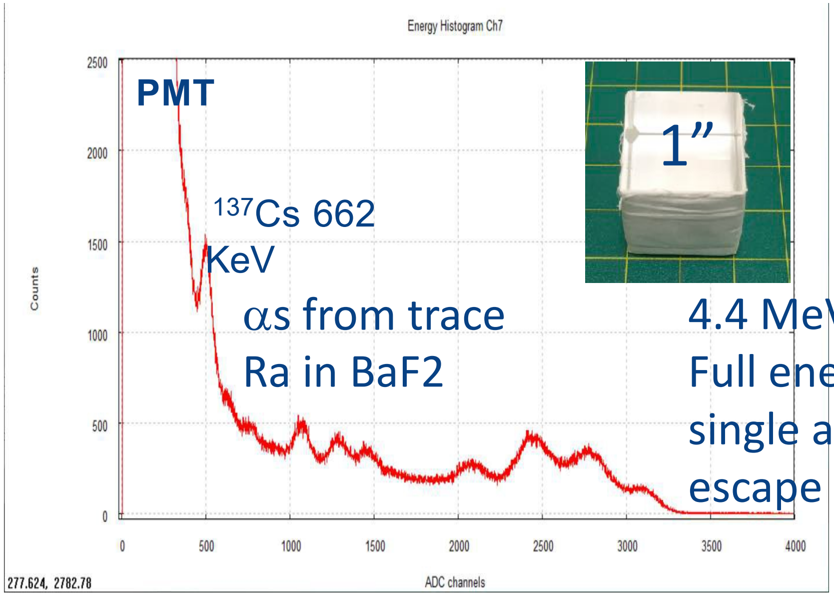
Calibrated with pulsed LED @ 465 nm for SiPM bias at 29 V

Excess noise factor determined at each bias



L. Zhang, J. Oyang

BaF_2 + AmBe Read out by PMT and FBK#611

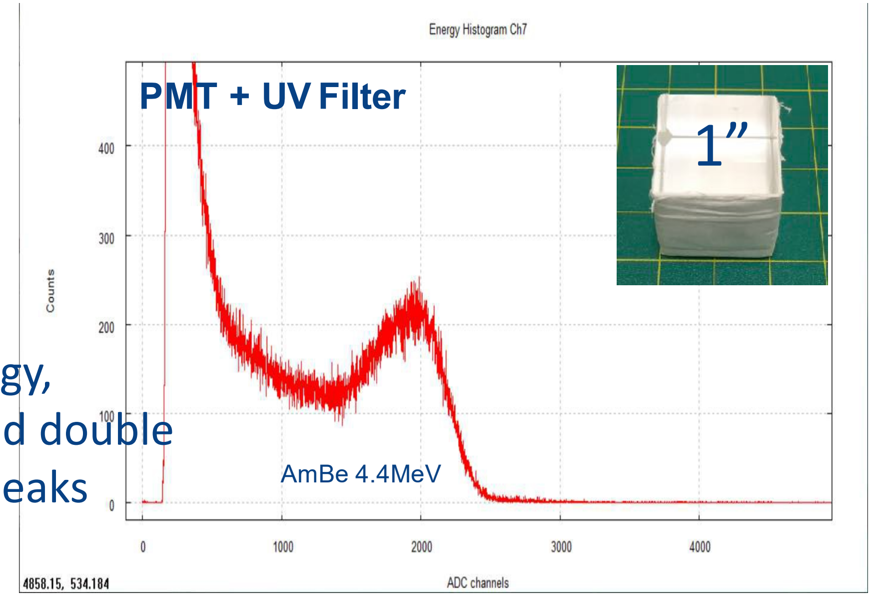


PMT

^{137}Cs 662 KeV

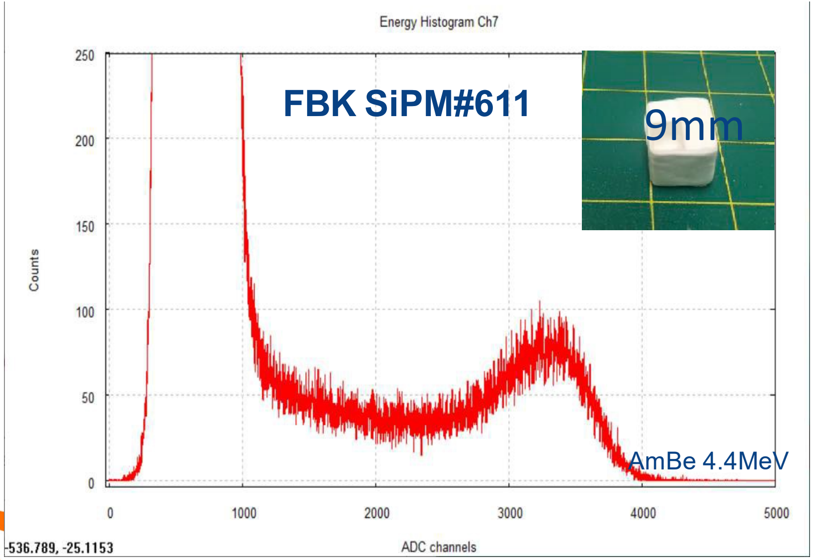
αs from trace Ra in BaF2

4.4 MeV
Full energy,
single and double
escape peaks



PMT + UV Filter

AmBe 4.4MeV

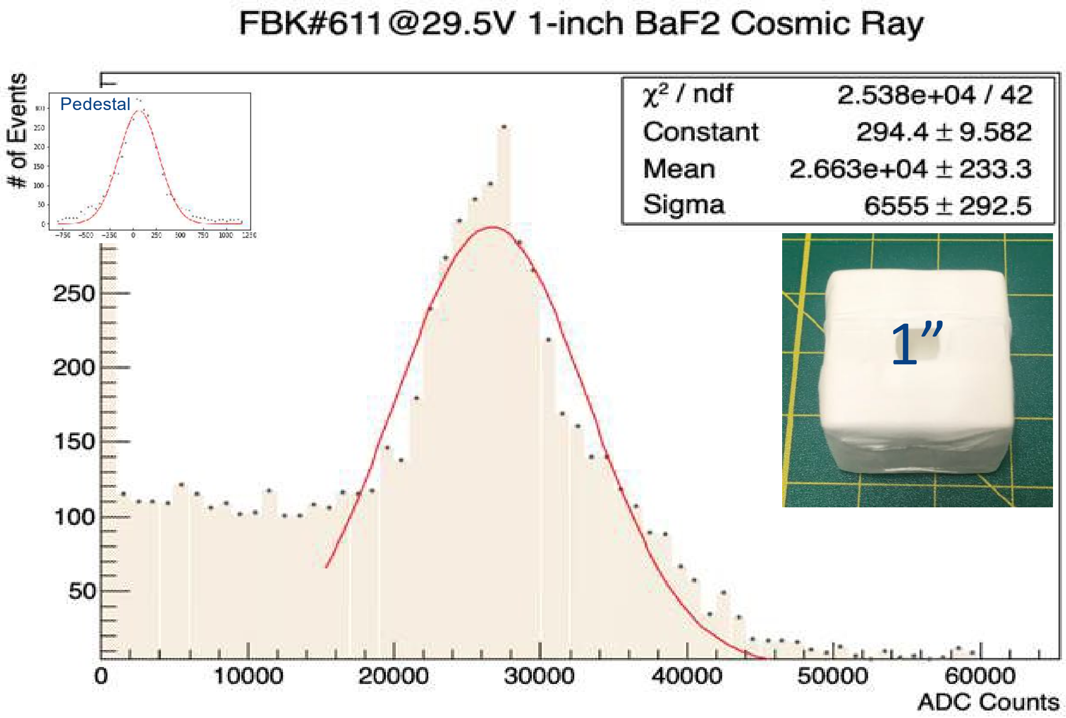


FBK SiPM#611

AmBe 4.4MeV

- 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

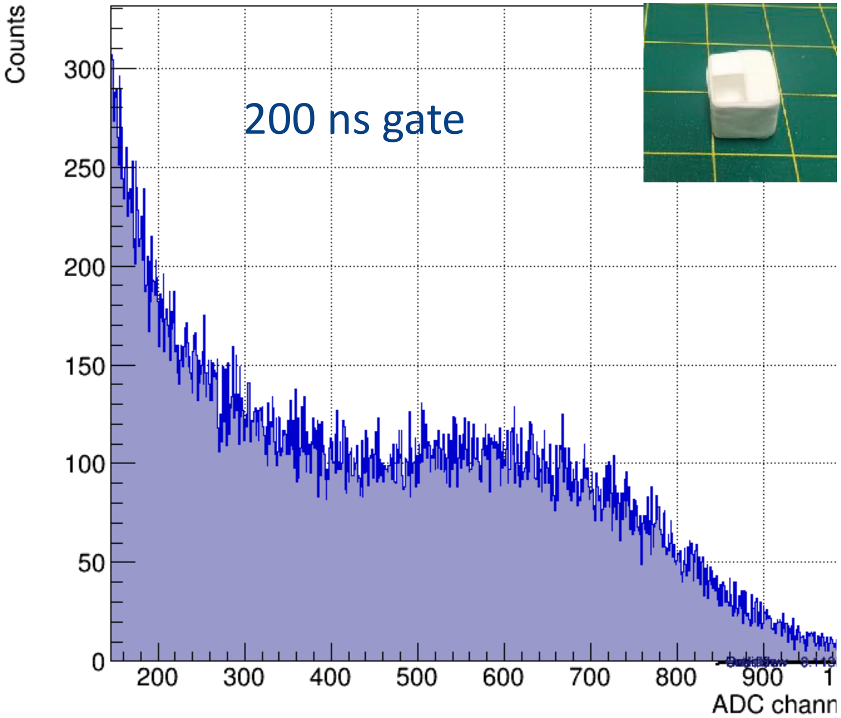
FBK #611 BaF_2 Cosmic Ray Spectrum

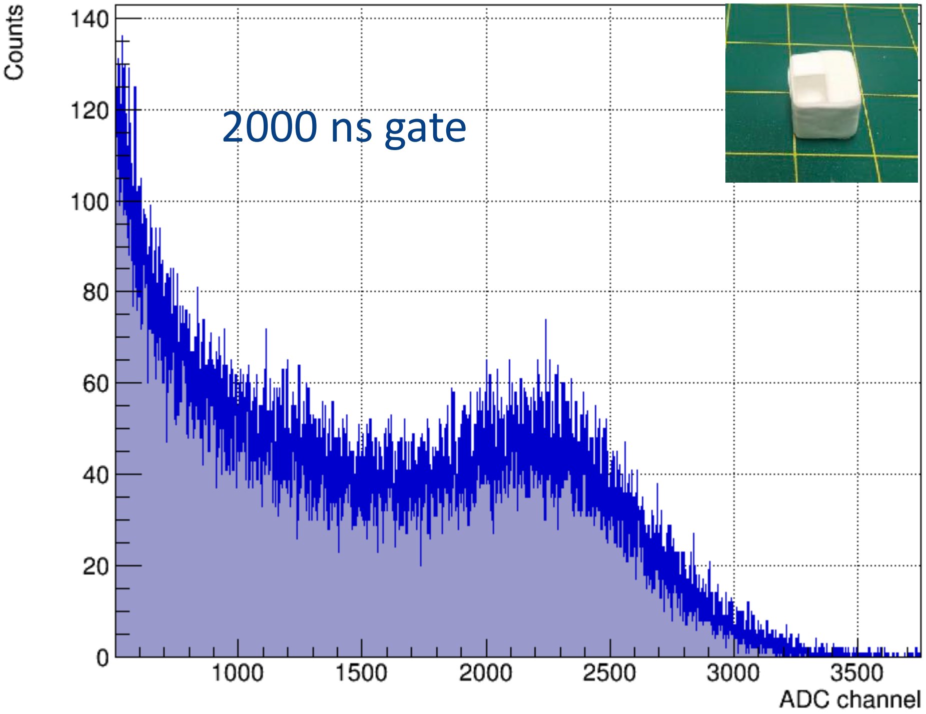


- FBK SiPM #611, dimension 6x6 mm, operated at 29.5V
- BaF_2 dimension 1” x 1” x 1”, wrapped with teflon with an opening of 6x6 (mm)
- Cosmic ray deposits 6.374 MeV/cm * 2.54 cm = 16.2 MeV
- (26631 - 68) adc / 148 pe/adc = 180 pe
- 180 pe / 16.2 MeV = 11 pe/MeV With 2x3 array, expect 60-70 pe/MeV

SiPM 611 BaF$_2$ with AmBe source (4.4 MeV)

9 mm BaF$_2$

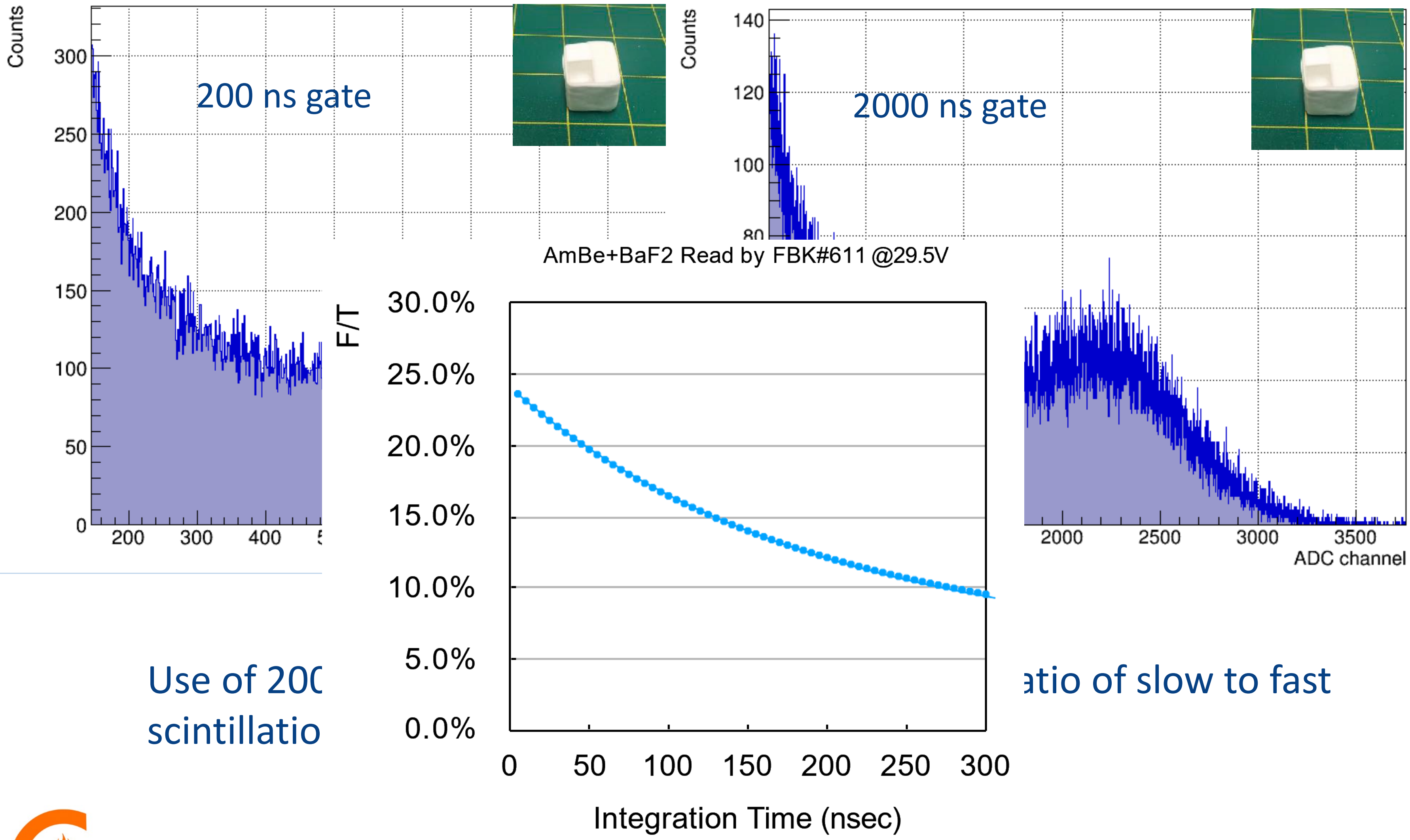




Use of 200 and 2000 ns gates allows extraction of ratio of slow to fast scintillation components seen by filtered SiPM: ~4

SiPM 611 BaF_2 with AmBe source (4.4 MeV)

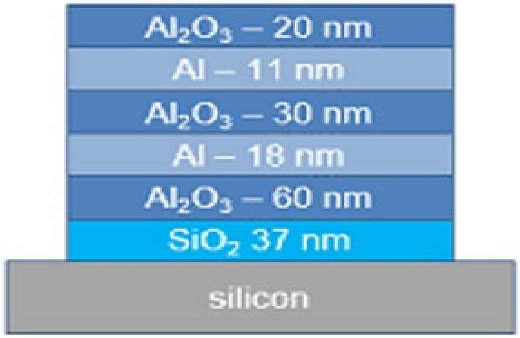
9 mm BaF_2

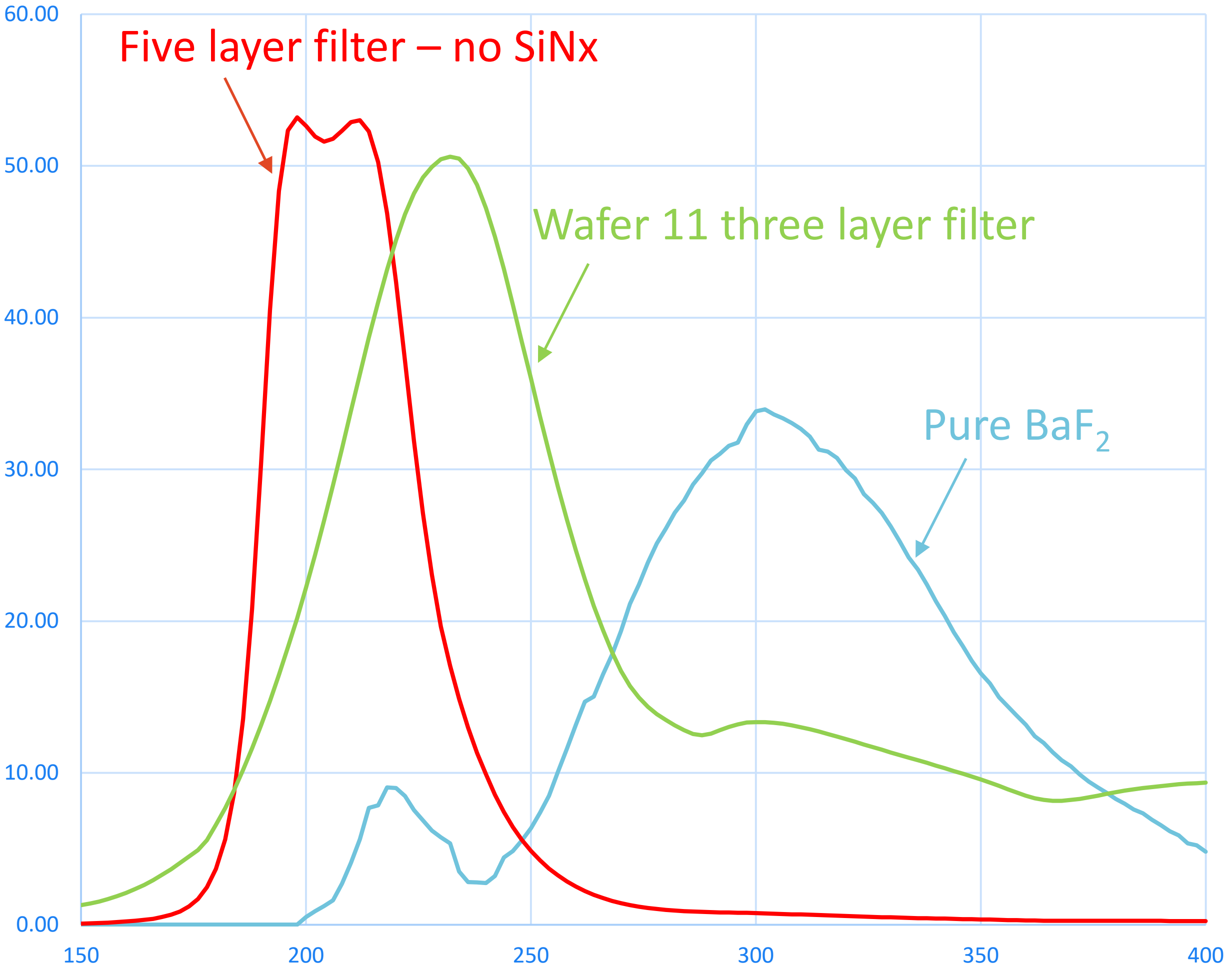


Use of 20(… atio of slow to fast
scintillatio

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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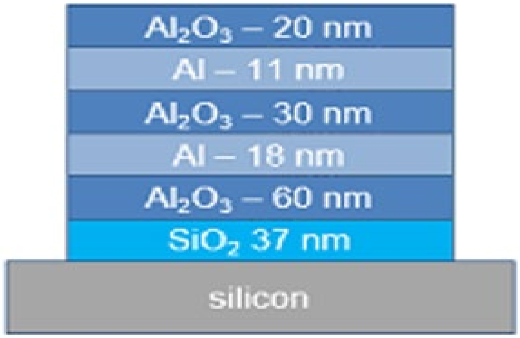
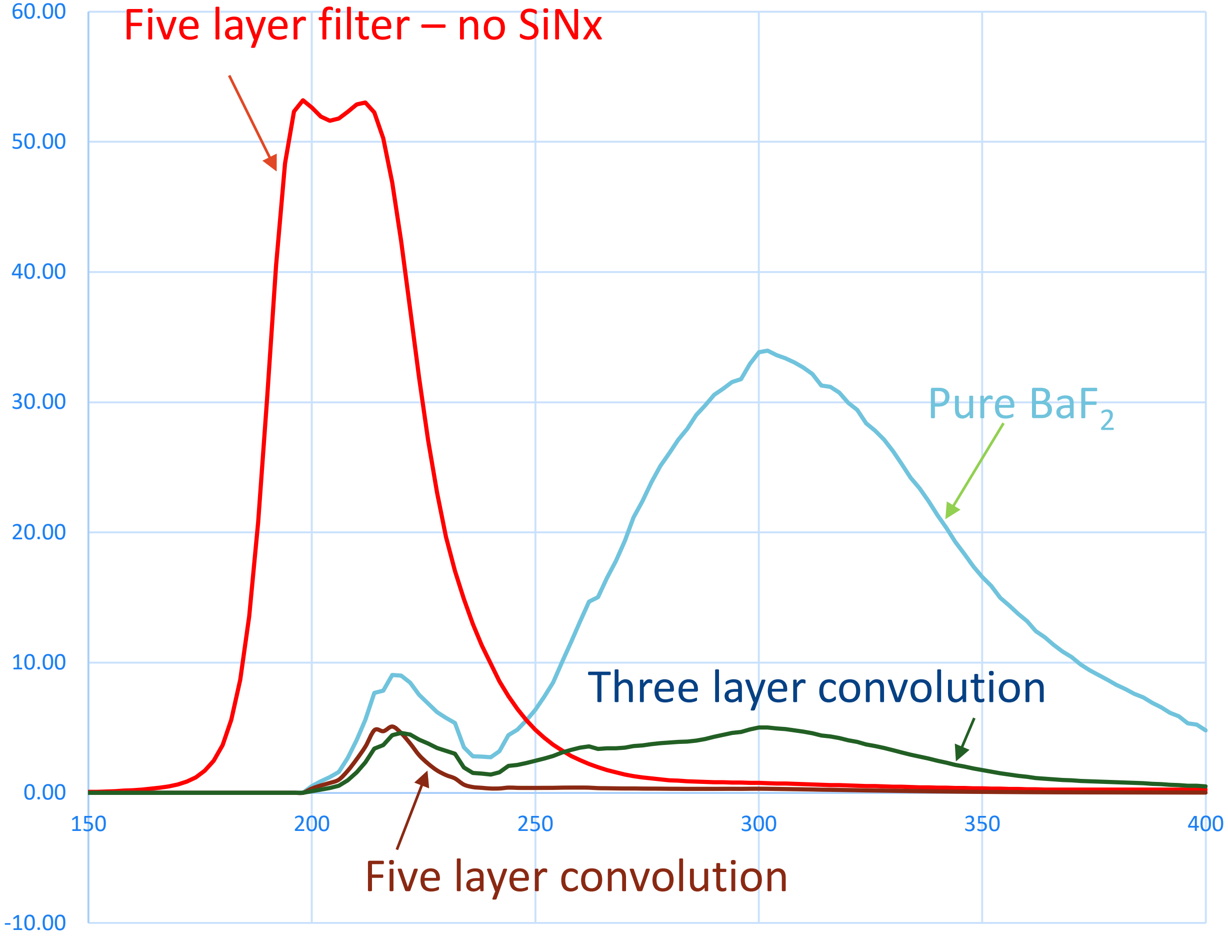


Al_2O_3 – 20 nm
Al – 11 nm
Al_2O_3 – 30 nm
Al – 18 nm
Al_2O_3 – 60 nm
SiO_2 37 nm
silicon



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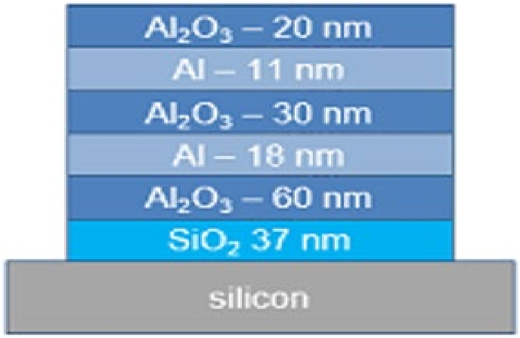
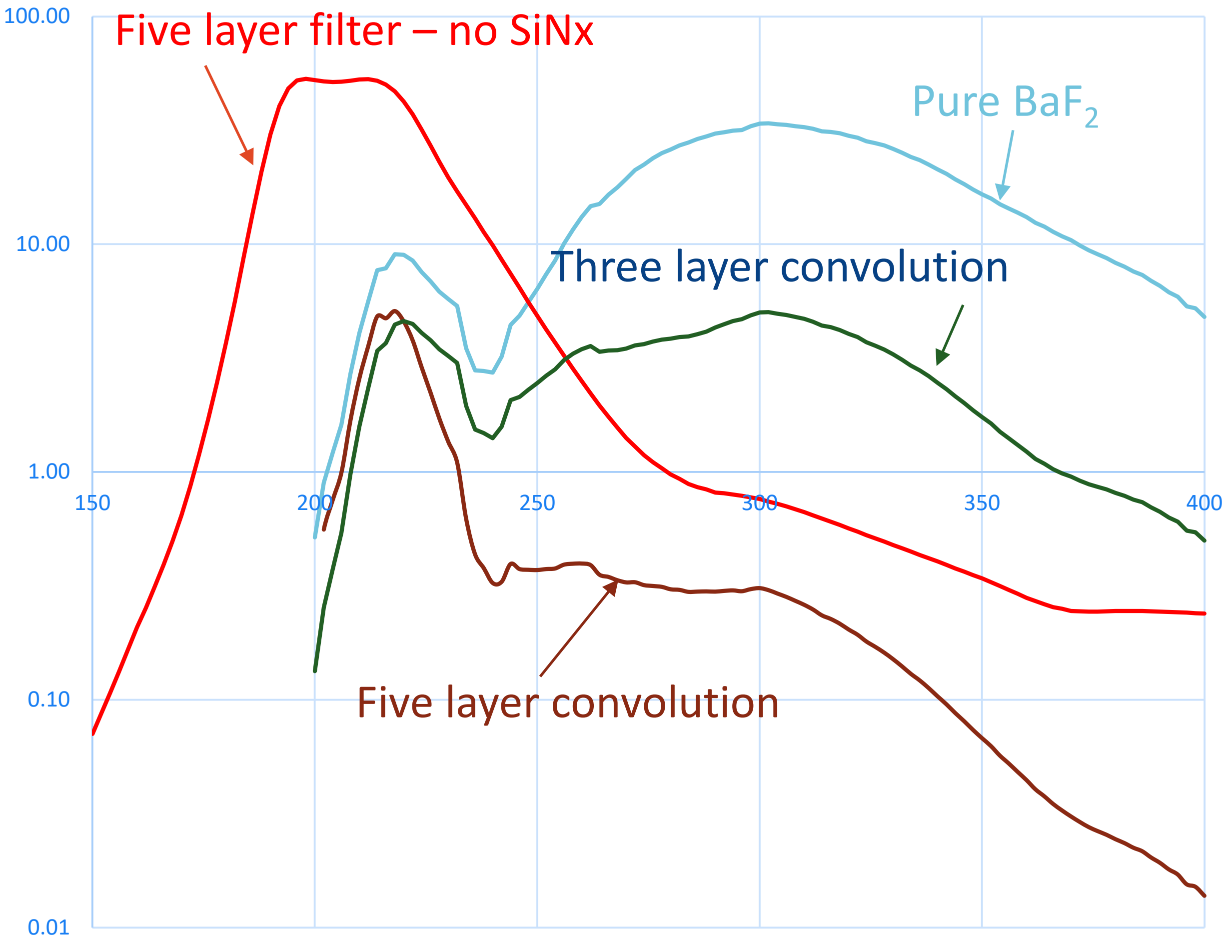
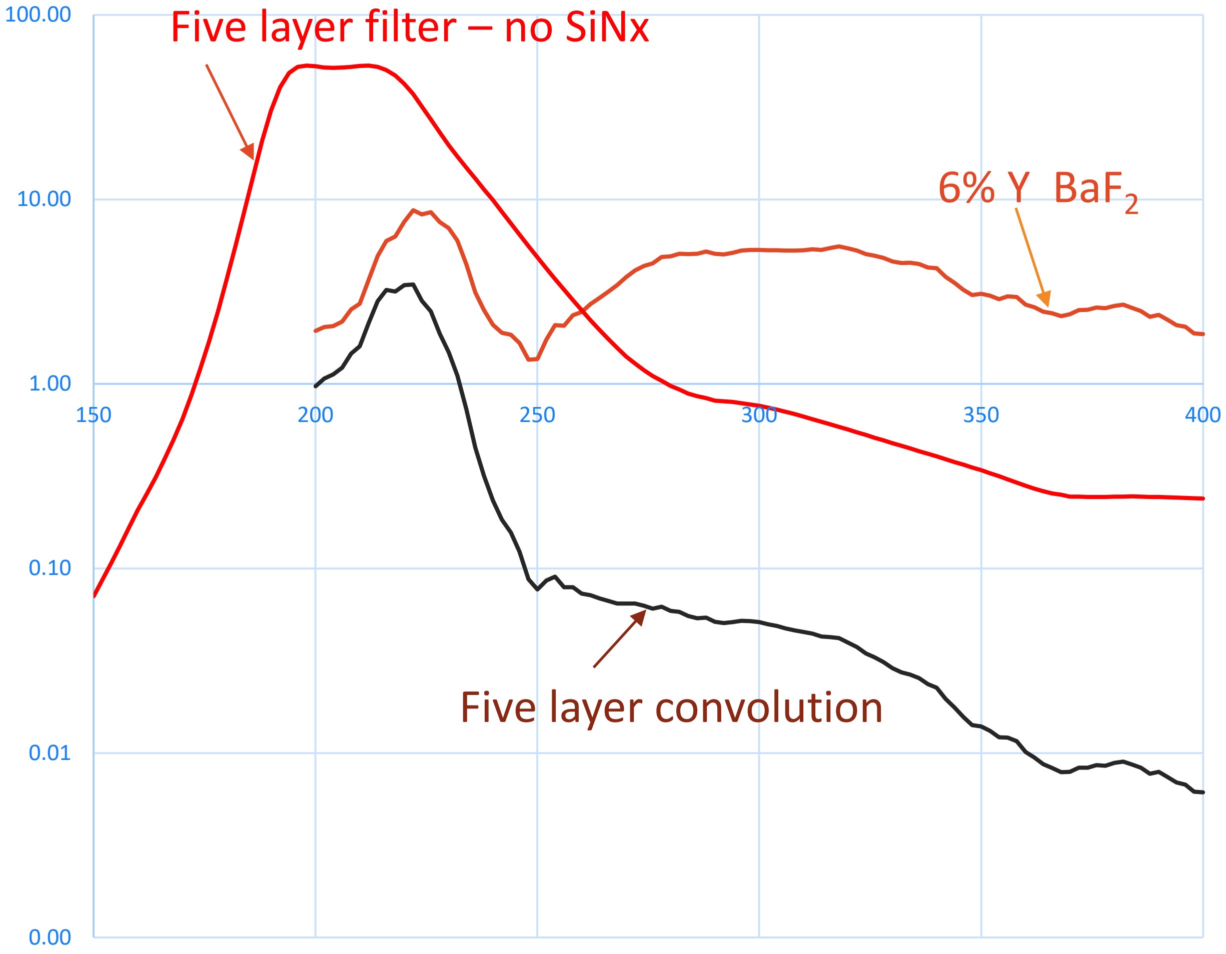




Further improvement of fast/slow performance

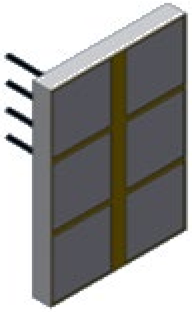
- Combining
  - 6% Y-doped BaF_2 and
  - SiPM with a five layer filter

  provides further improvement in the ratio of fast to slow scintillation components
- This provides enabling performance for the calorimeter of the Mu2e-II upgrade



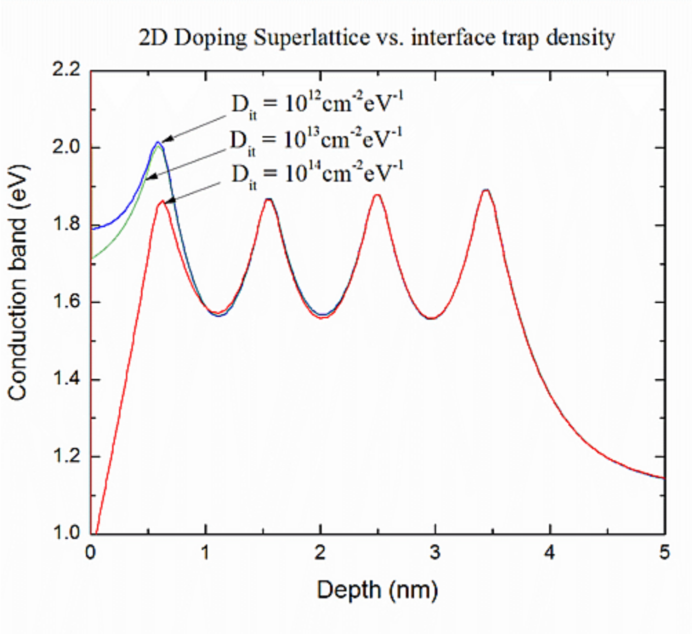
Current status and plans

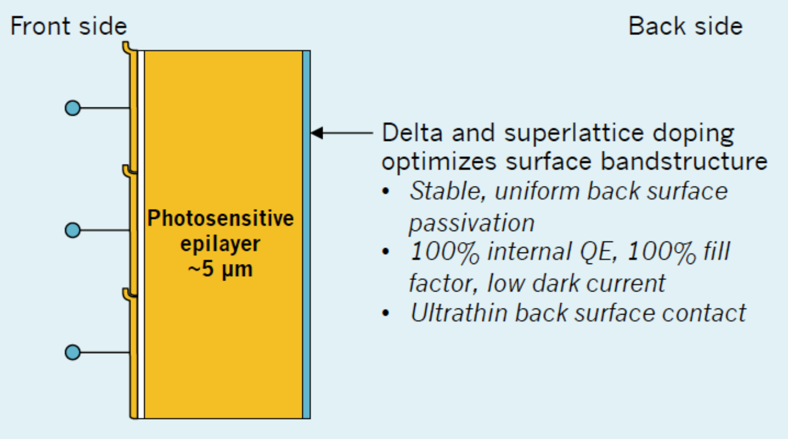
- Next steps
  - Spectra with Y-doped BaF_2 crystals, slow fast scintillation yield
  - Use 3 x 2 chip array of 6x6mm chips in series/parallel configuration with larger crystals
  - Radiation hardness studies with γs and neutrons
  - MTF burn-in studies
  - Fab more sophisticated five-layer filters on remaining wafers
  - 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



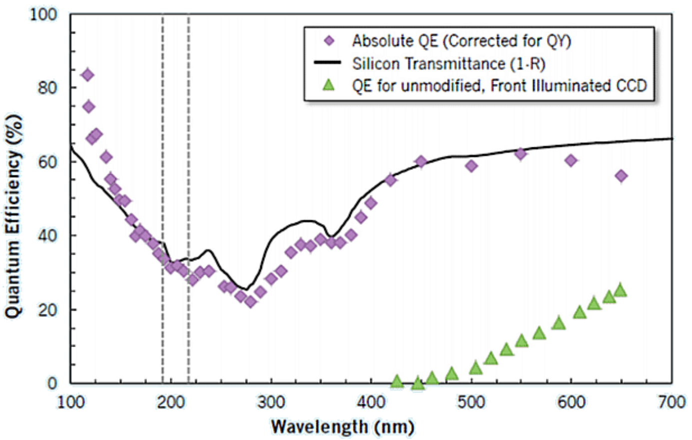


Delta and superlattice doping optimizes surface bandstructure

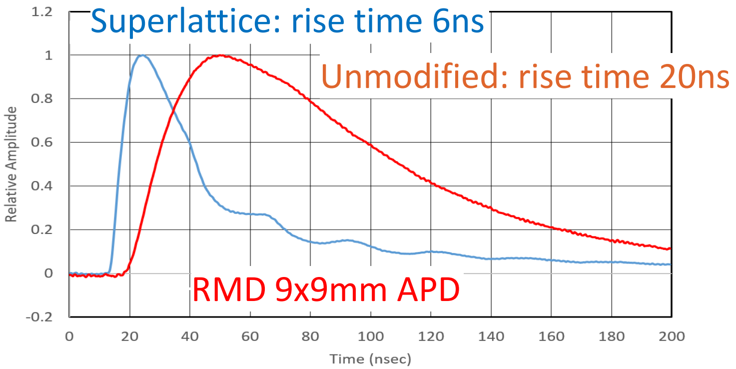
- *Stable, uniform back surface passivation*
- *100% internal QE, 100% fill factor, low dark current*
- *Ultrathin back surface contact*

Superlattice performance improvements

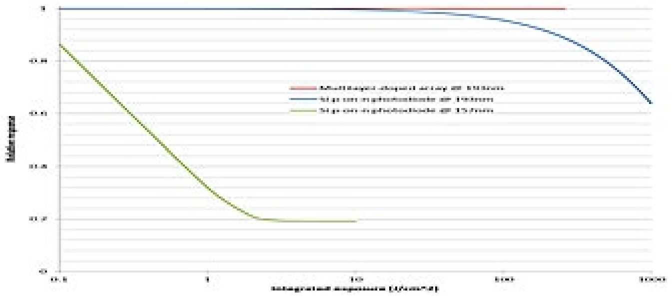
- Recombination of photoelectrons is suppressed by quantum exclusion, resulting in close to 100% internal QE
    - Quantum efficiency in the 200-300 nm region approaches the silicon transmittance (1-R) limit



- 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 is ~ 1-10 J/cm^2



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

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 < 1ns 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 and neutrons