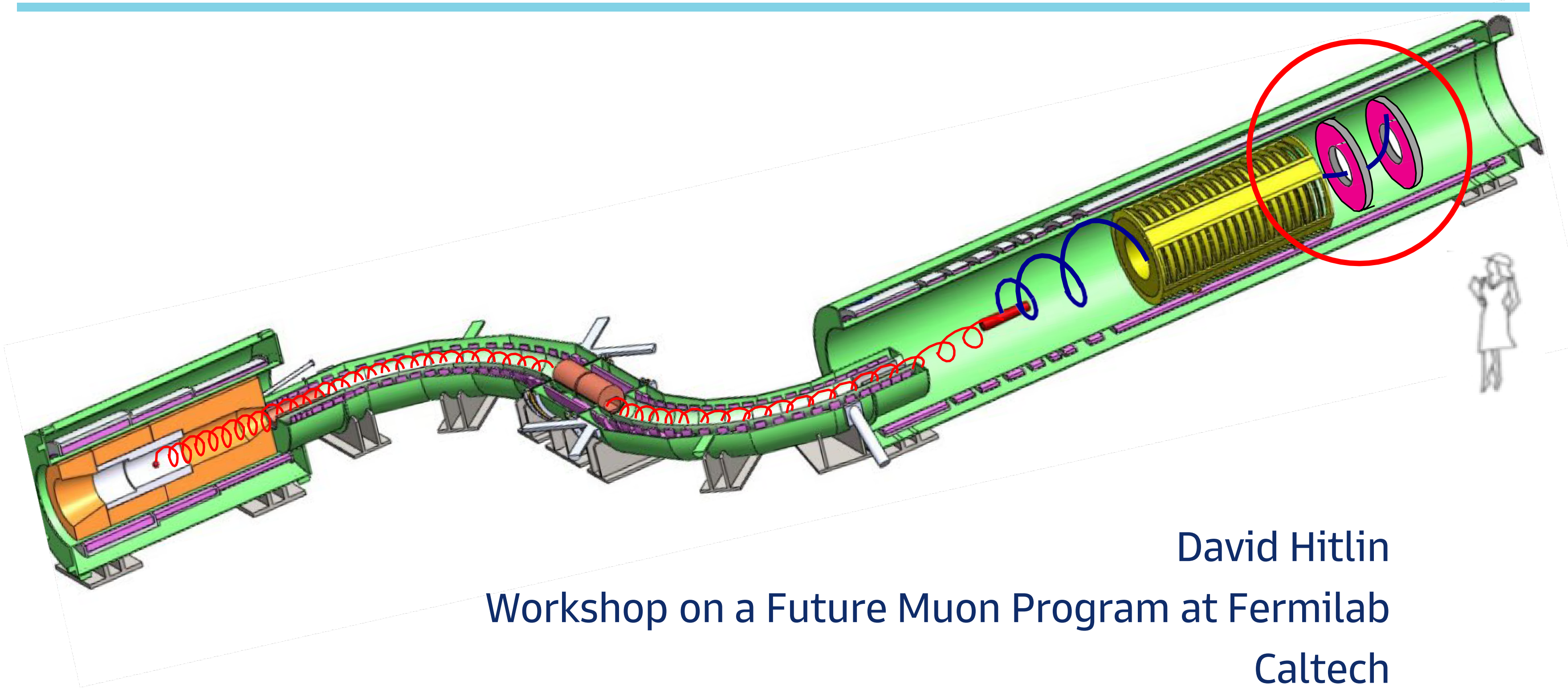
Photosensors for barium fluoride readout



David Hitlin
Workshop on a Future Muon Program at Fermilab
Caltech
March 28, 2023

Nominal Mu2e-II Calorimeter Requirements

The Mu2e-II calorimeter will see higher rates, higher neutron flux and a higher ionizing dose on the photosensors

X 10 Factor

Disk 1
Inner: (10x2x5x3) → 300 krad
Outer: (10x0.5x5x3) → 75 krad

Disk 2
Inner: (10x1x 5 x 3) → 150 krad
Outer = (10x0.5x5x3) → 75 krad

Latest SiPM Dose test indicated no hints of deterioration up to 80 krad

X 10 Factor

Disk 1 = $10 \times 6 \times 10^{10} \times 5 \times 3 = 9 \times 10^{12}$

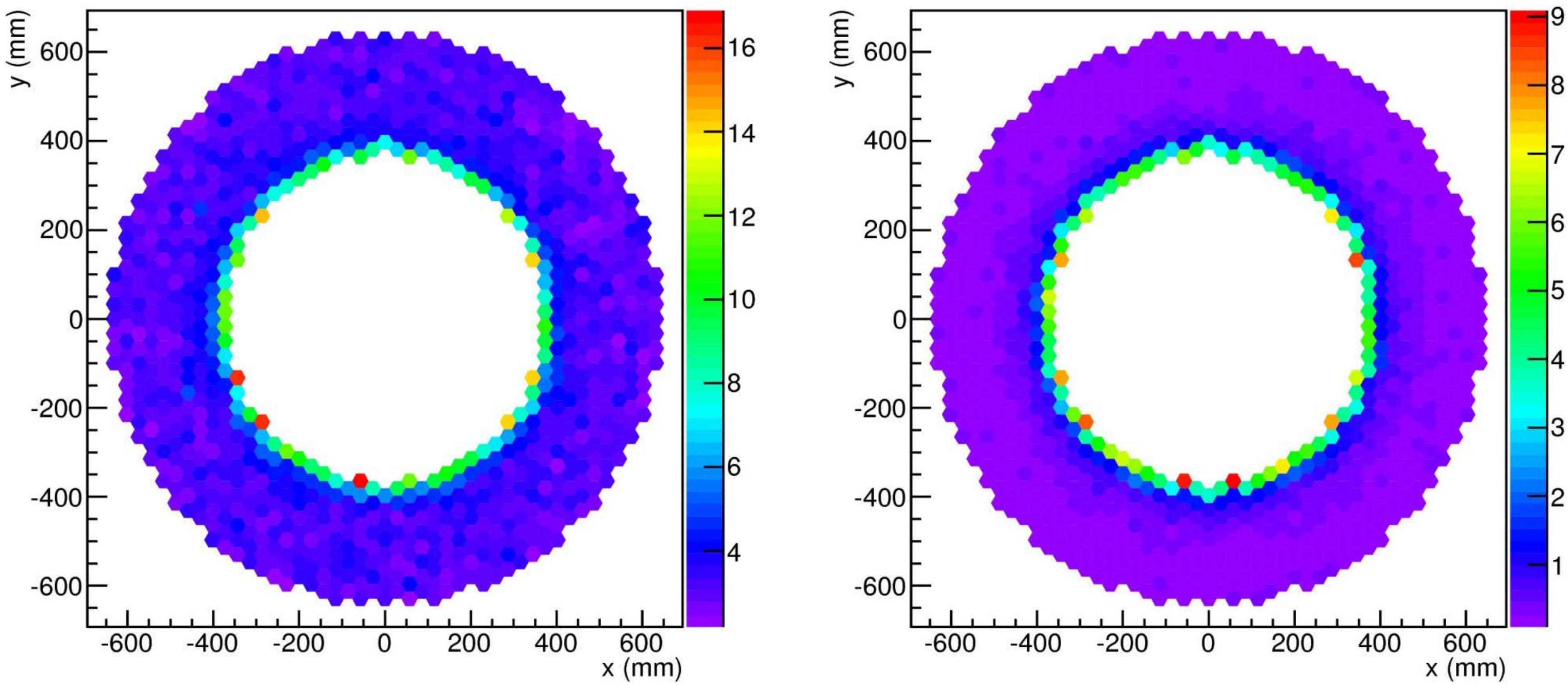
Neutron fluence up to 10^{13} n_1MeV/cm^2 → -40 C

We need, at least in the inner part of the calorimeter, a faster, more radiation hard scintillator, an appropriate photosensor, and a data acquisition system that can support the crystal/sensor performance

We have the needed simulation tools exist to explore the Mu2e-II parameter space
We then need to formulate an R&D program aimed at finding viable solutions

Dose per crystal in kRad/year (Mu2e)

Disk 1 Disk 2



The average dose is around 3 (0.5) kRad / year for the front (back) disk, up to 16 (9) kRad / year for the innermost crystals in the front (back) disks

Echenard

Fast Inorganic Scintillators

	GSO	YSO	LSO/ LYSO	CsI	BaF_2	CeF_3	$CeBr_3$	$LaCl_3$	$LaBr_3$
Density (g/cm^3)	6.71	4.44	7.4	4.51	4.89	6.16	5.23	3.86	5.29
Melting point (°C)	1950	1980	2050	621	1280	1460	722	858	783
Radiation Length (cm)	1.38	3.11	1.14	1.86	2.03	1.7	1.96	2.81	1.88
Molière Radius (cm)	2.23	2.93	2.07	3.57	3.1	2.41	2.97	3.71	2.85
Interaction Length (cm)	22.2	27.9	20.9	39.3	30.7	23.2	31.5	37.6	30.4
Weighted Z value	57.9	33.3	64.8	54	51.6	50.8	45.6	47.3	45.6
dE/dx (MeV/cm)	8.88	6.56	9.55	5.56	6.52	8.42	6.65	5.27	6.9
Peak Emission [a] (nm)	430	420	420	420 310	300 220	340 300	371	335	356
Refractive Index[b]	1.85	1.8	1.82	1.95	1.5	1.62	1.9	1.9	1.9
Relative Light Yield[a]	45	76	100	4.2 1.3	42 4.8	8.6	99	15 49	153
Decay Time[a] (ns)	73	60	40	30 6	650 0.6	30	17	570 24	20
d(LY)/dT [d] (%/°C)	-0.4	-0.1	-0.2	- 1.4	-1.9 0.1	~0	-0.1	0.1	0.2

a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. Relative light yield normalized to the light yield of LSO
d. At room temperature (20°C) #. Softening point

1. http://www.detectors.saint-gobain.com/Plastic-Scintillator.aspx

http://pdg.lbl.gov/2008/AtomicNuclearProperties/HTML_PAGES/216.html

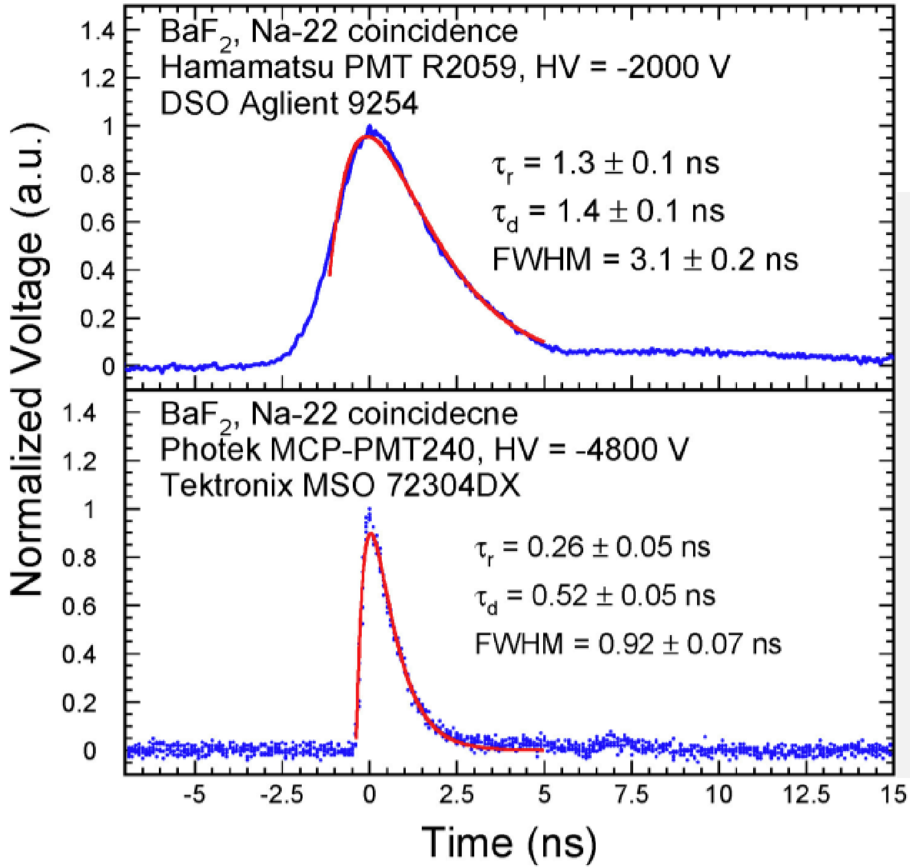


FIG. 19. A comparison of BaF_2 pulse shape measured with a Hamamatsu R2059 PMT (top) and a Photek MCP-PMT 240 (bottom).

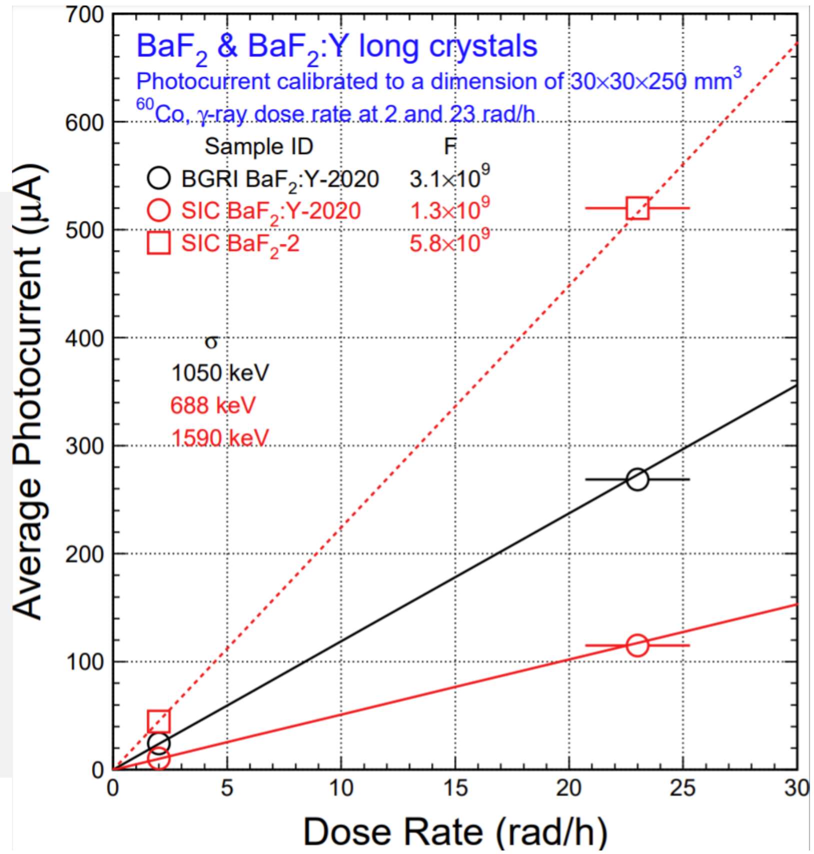
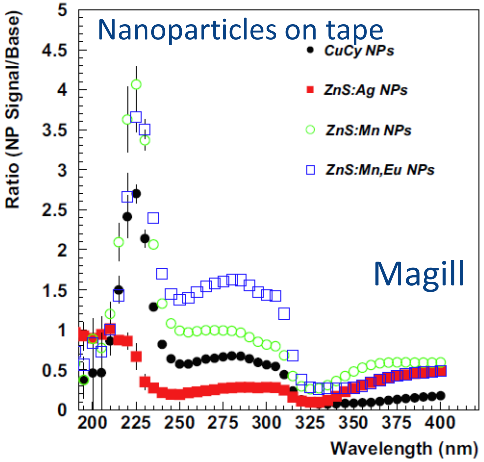


FIG. 21. Photocurrent is shown as a function of the dose rate for an SIC BaF_2 and two BGRI and SIC BaF_2:Y samples of calorimeter size under ionization dose rate of 2 and 23 rad/h.

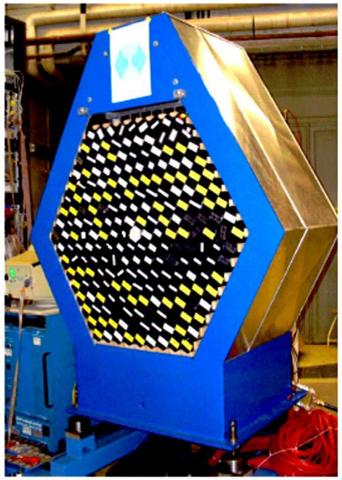
Zhu

Photosensor options for Y-doped BaF_2

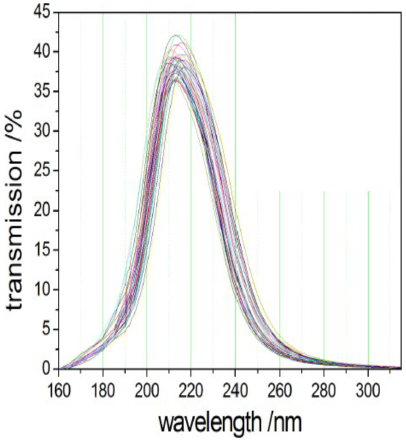
- We still lack an ideal photosensor for the rates of Mu2e-II
- What is required of an appropriate photosensor?
    - Spectral sensitivity in the 200 nm region for best energy and time resolution
    - Fast/slow component discrimination for high rate capability
    - Improved rise/fall time characteristics to fully capitalize on the fast component native time resolution and rate capability
    - Radiation hardness (photons/neutrons)
    - Must work in a 1T magnetic field
- Photosensor candidates
    - External filters or nanoparticle wavelength shifters
    - Integrated filters
        - Large area APD, having high PDE at 220nm and strong suppression at 320nm developed at Caltech/JPL/RMD
            - These have larger dark current and more noise than standard RMD devices, but could 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
    - MCPs
        - LAPPDs such as those from Incom, with solar blind photocathodes
        - AlGaN photocathodes + MCP (Dubna)

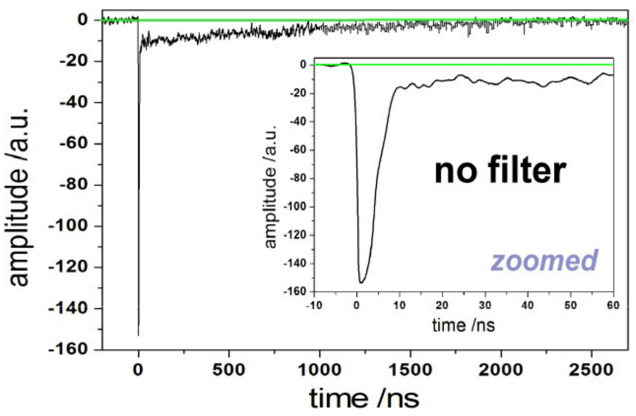


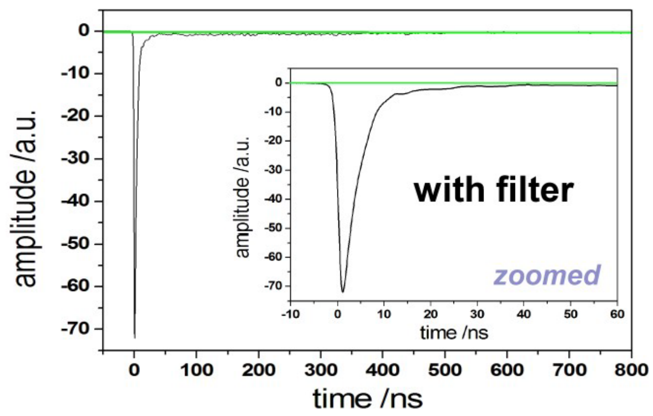
PMT + external filter



- The TAPS experiment at ELSA at Mainz (no B field) has for many years had a BaF_2 forward calorimeter, reading out both fast and slow components with HR2059-01 PMTs
    - They use an integration time of 2μs; they are thus limited to a single crystal rate of ~100kHz
- An upgrade must cope with increased rates, so they eliminate the slow component using a bandpass filter centered at 214 nm with a transmission at λ_{max} that varies from 36 to 42%
- Elimination of the slow component allows a gate of 20ns, with a resulting single crystal rate capability up to ~2 MHz







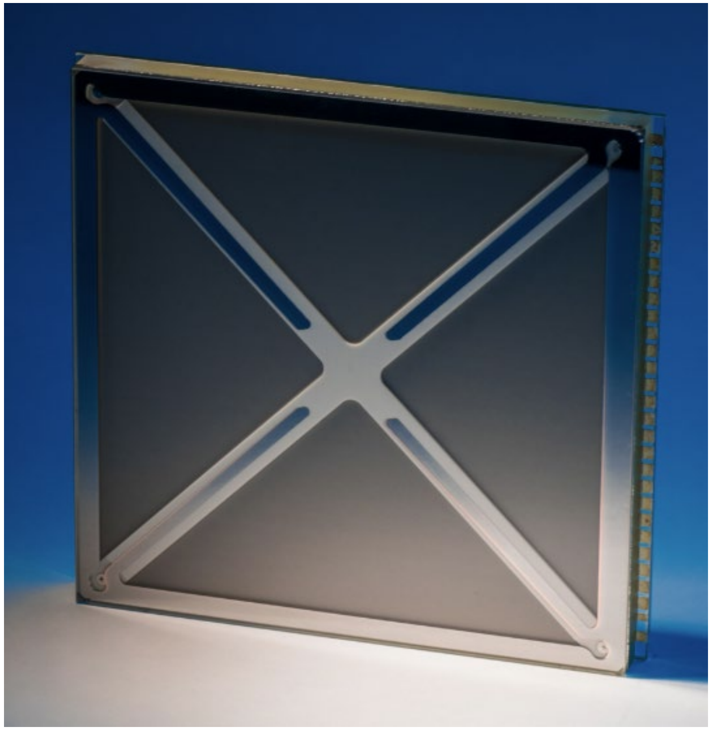
S. Diehl, R.W. Novotny, B. Wohlfahrt and R. Beck, CALOR 2014

An external filter can also be used with an appropriate solid state photosensor (*cf* S. Magill)
However, a filter that is integrated with the silicon sensor can achieve greater efficiency)

LAPPD with a solar blind photocathode

- The best way to take full advantage of the BaF_2 fast component in a magnetic field is a microchannel plate device.
  The LAPPD, a channel plate PMT now produced by Incom in a 20x20cm form factor, is very fast and potentially very attractive, although still quite expensive, but much R&D remains before there is a practical device for use with BaF_2
  - Quartz entrance window
  - Cs-Te or AlGaN photocathode
  - A size appropriate to the scintillating crystal Molière radius
  - An affordable price

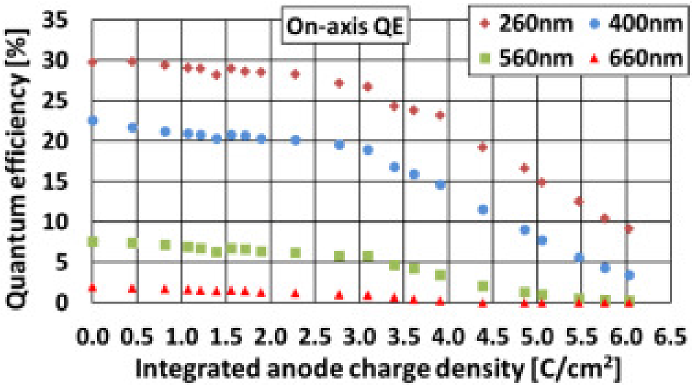
  Caltech and ANL made an abortive attempt to develop such a device using existing equipment but it was killed when ANL HEP Division management changed



The total charge at the anode of the MCP for Mu2e-II is likely to substantially exceed the microchannel plate limit of ~5-10 C/cm^2, even with an ALD MCP.
The lifetime of solar blind photocathodes is also a question.

MCP PMTs for BaF_2

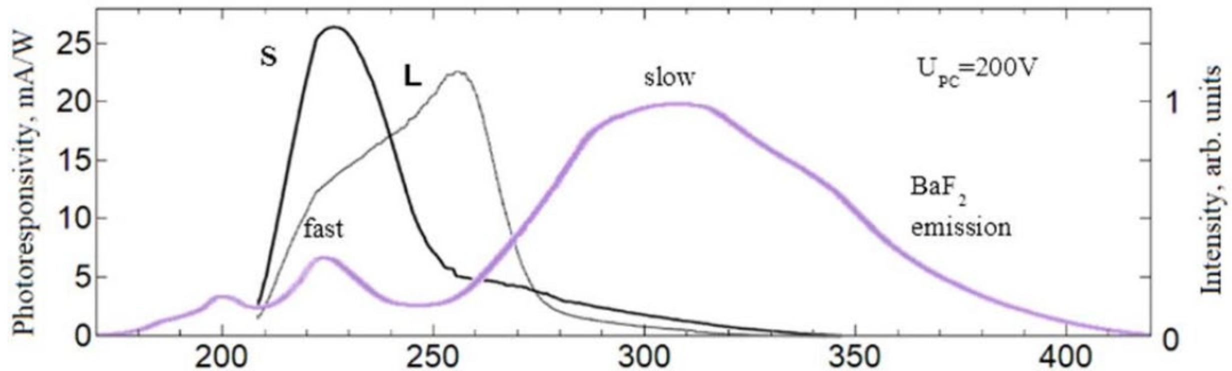
- Microchannel PMTs are an attractive photosensor for BaF_2 readout
  - Large area
  - High gain
  - Work in a magnetic field
  - Capable of 30ps timing
  - With ALD coating, there is a factor of two gain reduction at 5 C/cm^2 collected at the anode

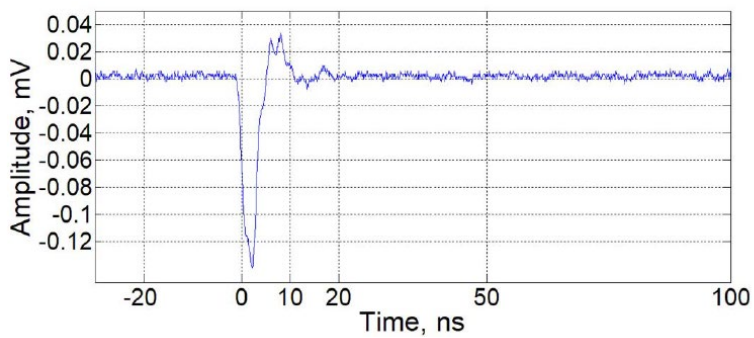


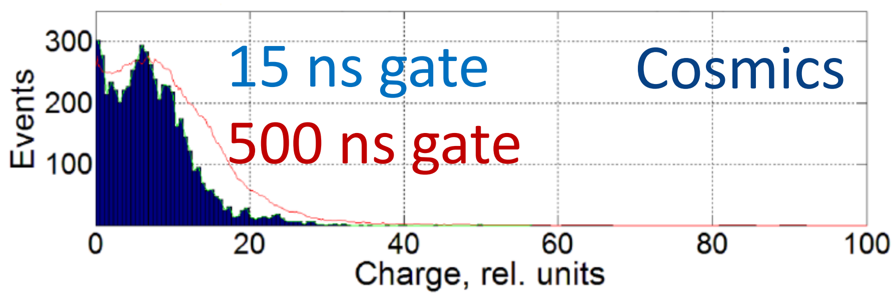
  - Barium fluoride scintillation emits 12,000 optical photons/MeV (fast+slow component)
    - A 10 krad exposure (100J/kG) to a 3x3x30 cm^3 crystal produces ~75 x 10^{18} photons, or 23 x 10^{16} pe at 10% geometric and 30% photocathode efficiency. With a 9 cm^2 cross section and a gain of 10^4, this is ~1.7 x 10^2 C/cm^2 collected at the anode

AlGaN photocathodes for an MCP

- AlGaN photocathodes have UV sensitivity and are solar-blind
- Have been used in astrophysics for years, QE_{opaque} ~30% at 220 nm
- Wide-band semiconductors such as AlGaN are radiation-hard







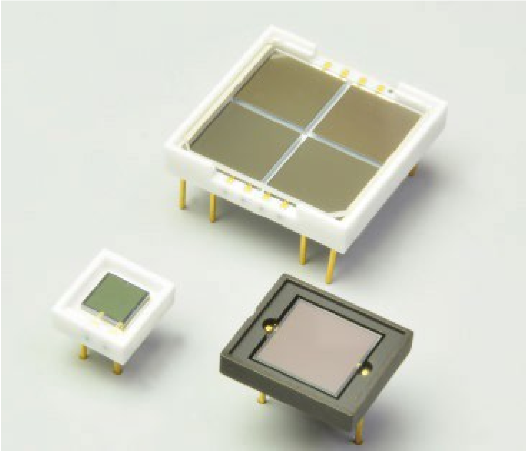
Need to measure the lifetime in total charge at the anode of the MCP of the MCP and of the AlGaN photocathode

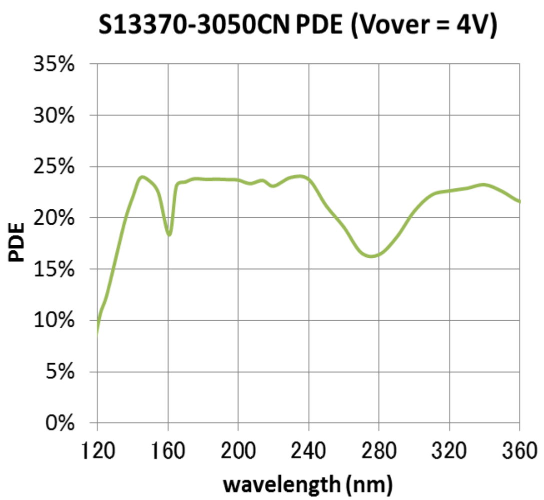
Atanov, et al.

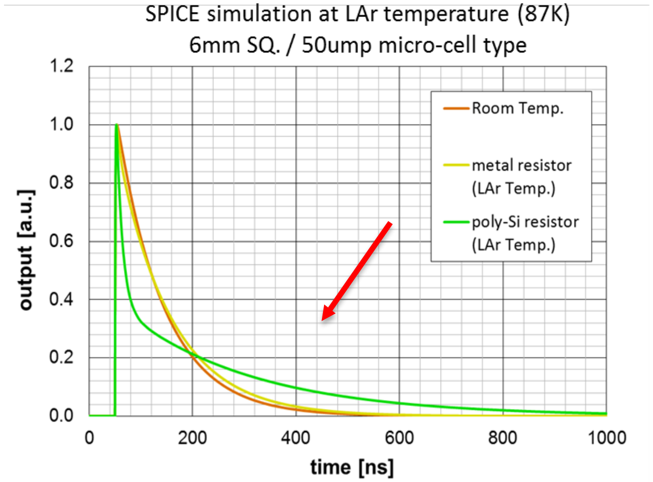
Hamamatsu VUV MPPC

<u>S13370 series</u>

- High PDE in VUV wavelength range
  - No slow/fast component discrimination
- Low optical crosstalk through trench structure
- Typical decay time of a large area device, dictated by RC
- 4@ 6x6mm
- Work at cryogenic temperatures



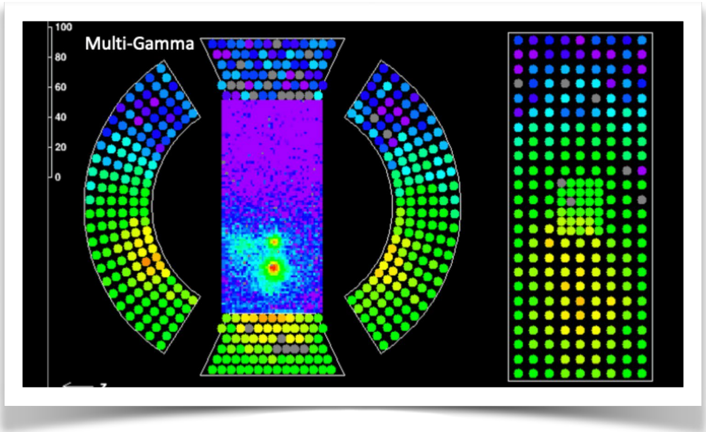




Series/parallel connection of 6x6 mm SiPMs, as in MEG-II and the current Mu2e calorimeter, improves decay time characteristics

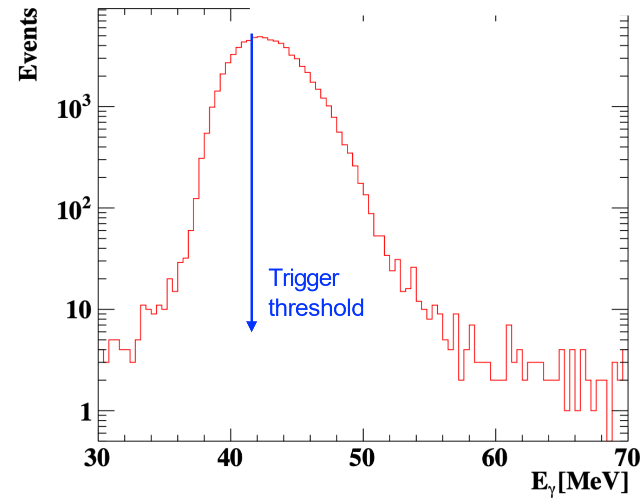
- FBK also has excellent VUV SiPMs

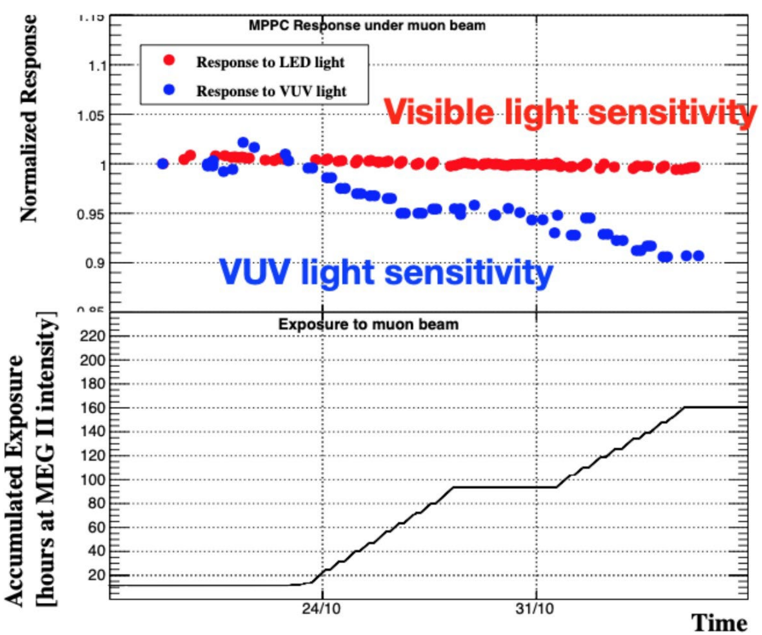
MEG-II Highlights - The LXe Calorimeter



In 2021, first data collected with full readout

PRELIMINARY





Degradation speed ~0.08%/hour

We observe a degradation of the PDE of MPPCs under beam

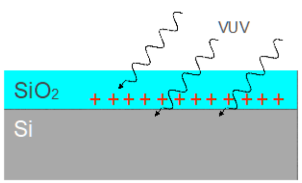
We successfully experimented a recovery procedure, to be repeated periodically (annealing by heat: we let the MPPCs drawing a large current when illuminated by LEDs, so to heat them by Joule effect up to 70 ºC for several hours)

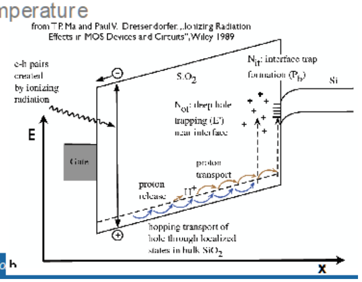
Francesco Renga - DISCRETE2021, Bergen, November 30, 2021

MEG-II Annealing

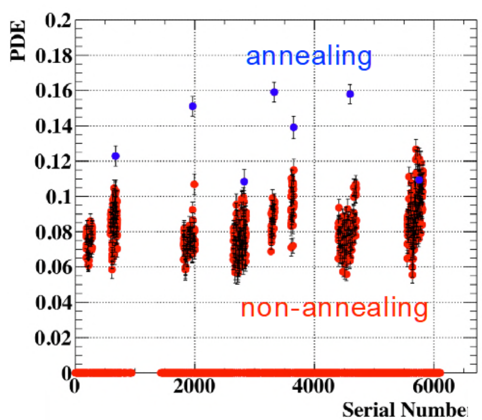
MPPC PDE Degradation

- 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?





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℃, 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

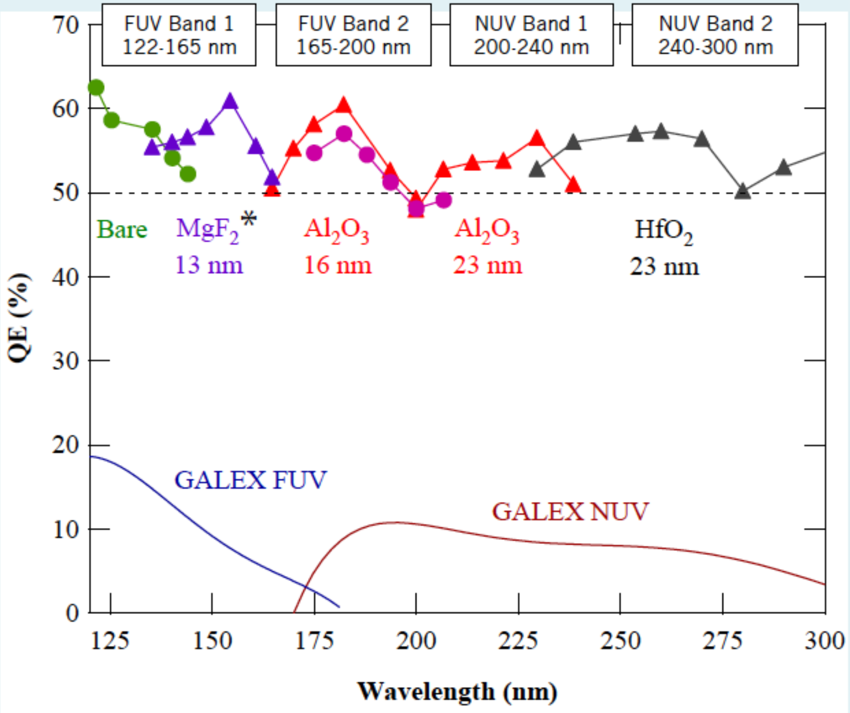
MPPC	Current [mA]	Time [hr]	PDE [%] 2018	PDE [%] 2019	Recovery
2763	20	22	7.9	9.8	1.24
2672	19-20	23	10.4	12.8	1.23
2802	17-19	23	9.1	11.5	1.26
2712	19	23	9.4	10.3	1.1
2789	19-24	38	9.5	13.8	1.45
2700	20-24	38	10.0	15.7	1.57
2658	21-24	38	8.8	15.3	1.74

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

There is another solution
to this problem. See below

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

CIT/JPL/FBK SiPM - a phased approach

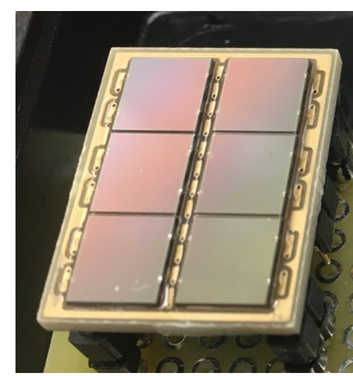
- BaF_2 fast component readout with an integrated filter
- Building on our experience with a large area APD developed with RMD, we have adopted a phased SiPM development approach

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

Underway
3. Improve slow component rejection with more sophisticated five-layer filters – devices at Caltech, in queue for measurement/test
4. Use delta doping and backside illumination to improve PDE, the effectiveness of the filter, timing performance and UV tolerance

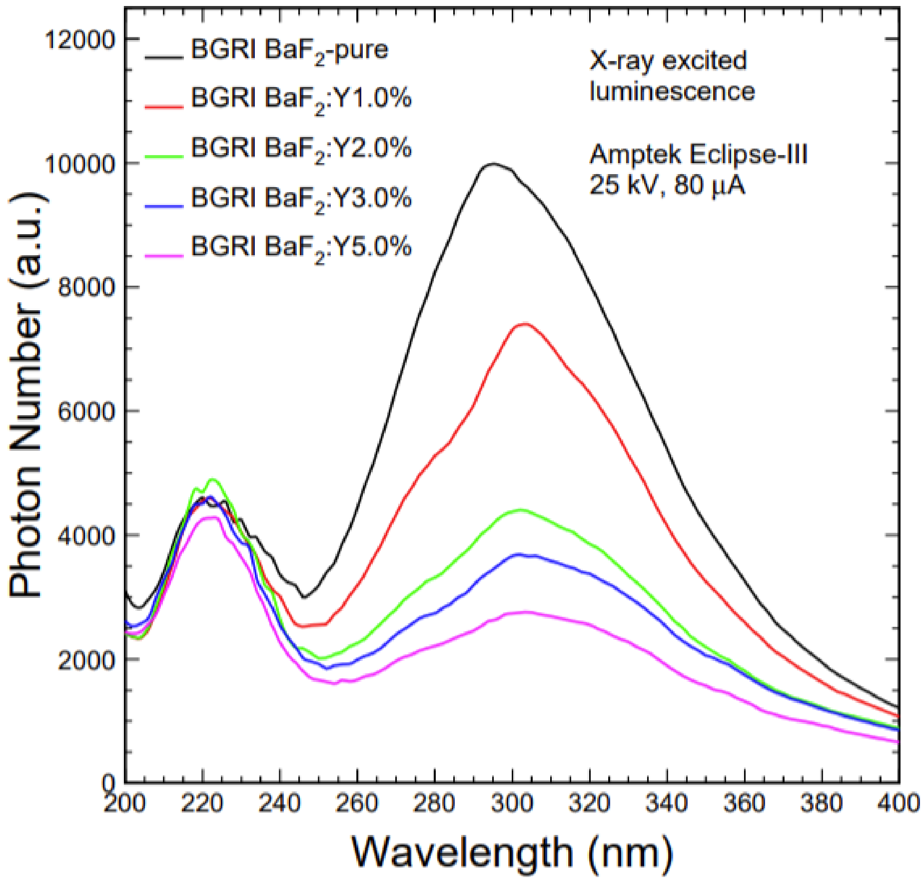
Underway
- First explore parameter space of MBE fab of delta-doping using diode structures of various sizes – wafers entering production

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



Configuration is identical to that for Mu2e:
2x3 array of 6x6mm devices with series/parallel biasing

Integrated three-layer filter on an FBK SiPM



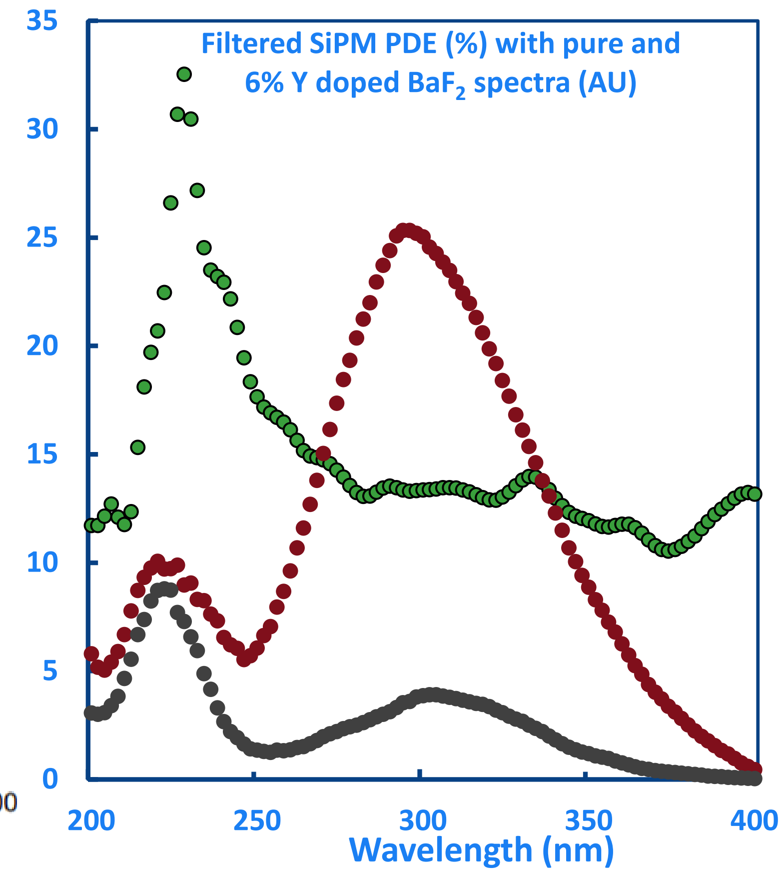
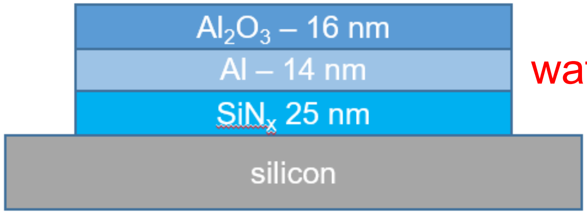


FIG. 20. X-ray excited emission spectra measured for BGRI BaF$_2$ crystal samples with different yttrium doping level.

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.

FBK SiPM with three-layer filter

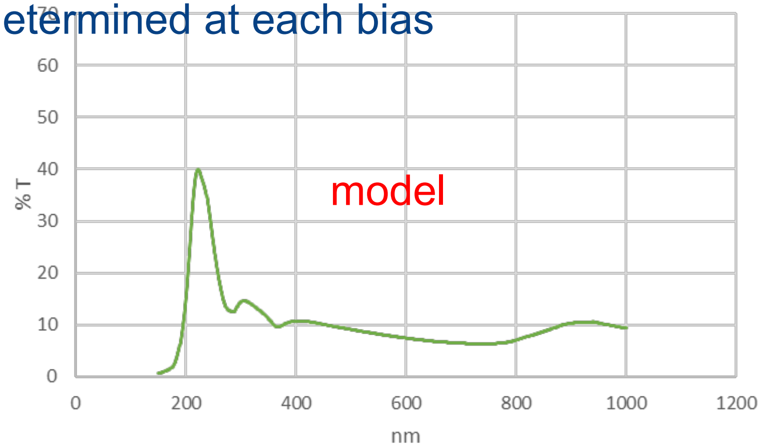


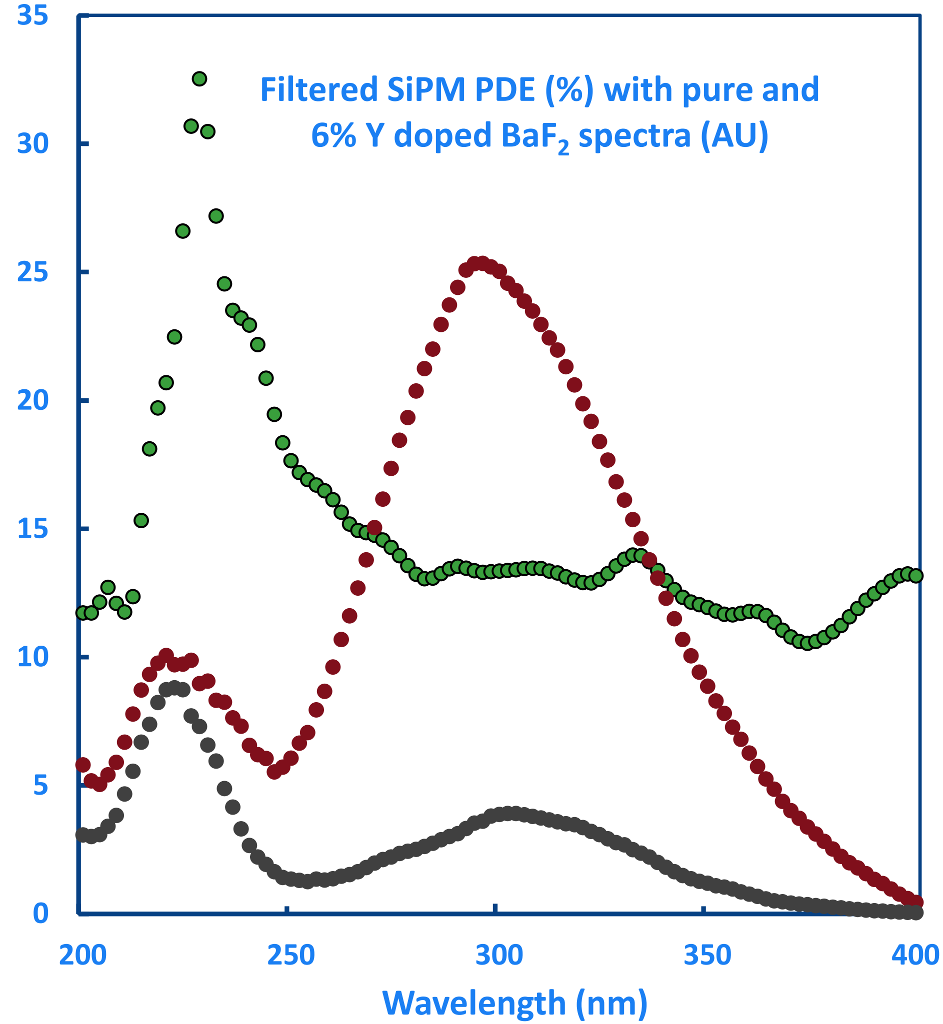
wafer 11

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

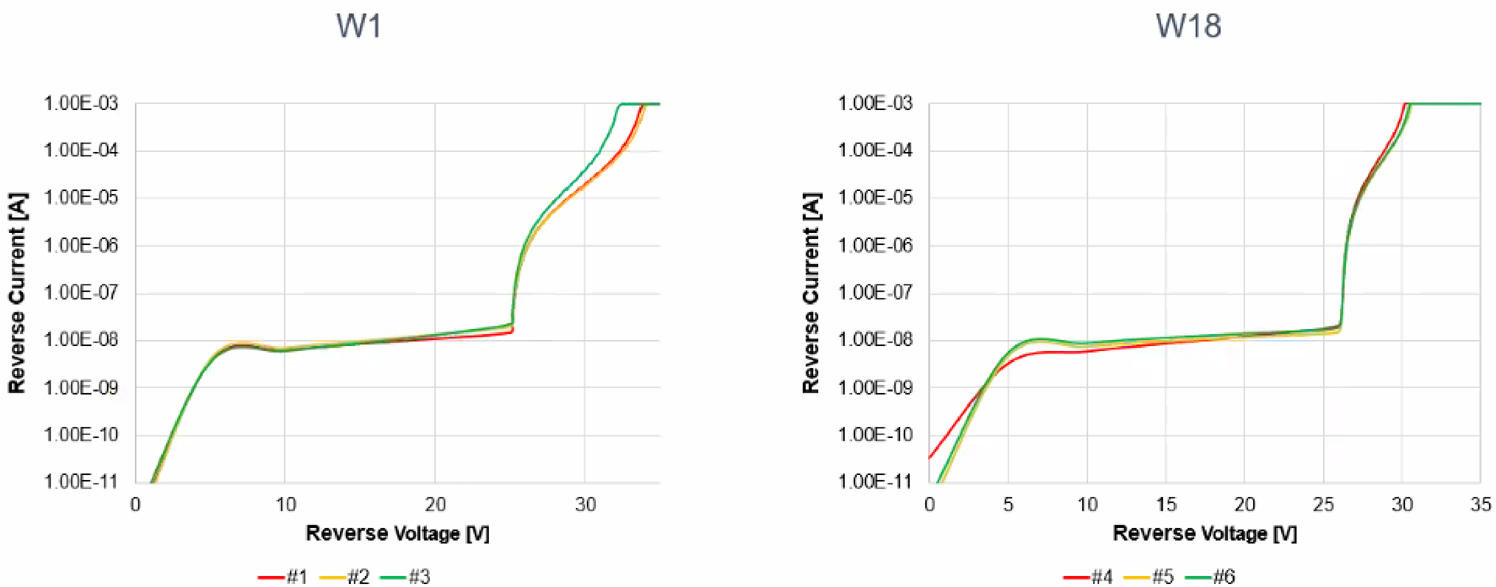




L. Zhang, J. Oyang

IV curves for new wafers

IV measurement



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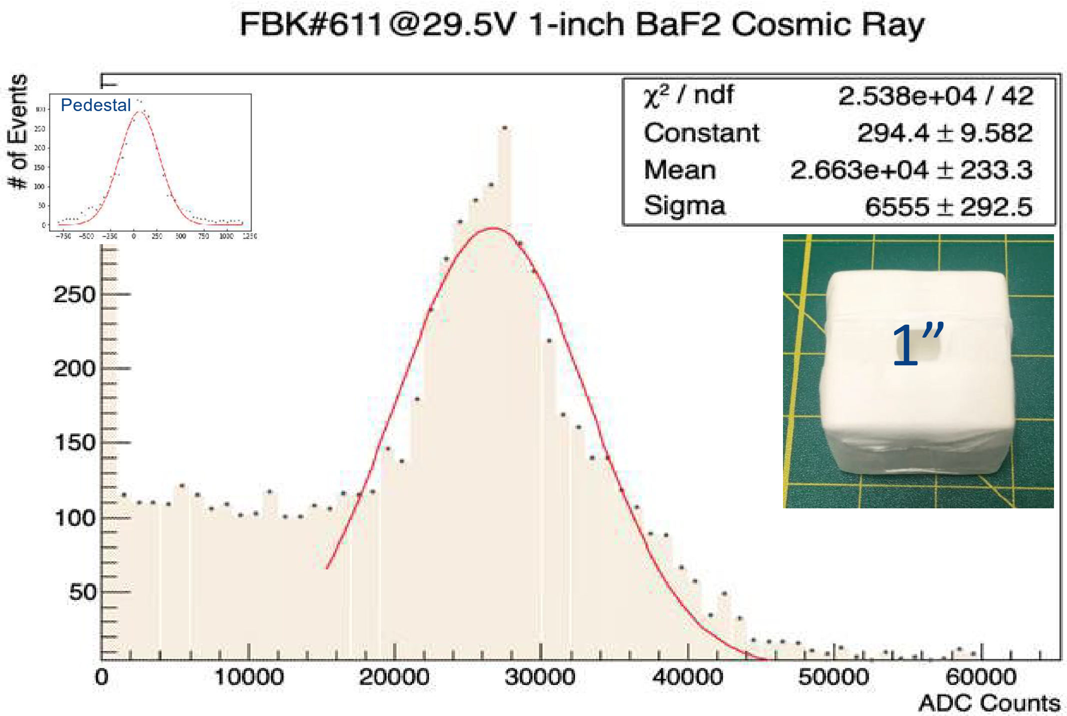
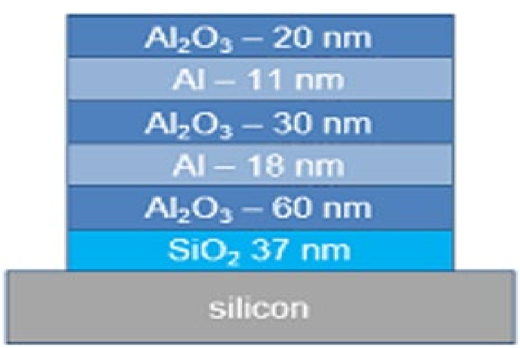
FBK #611 BaF_2 Cosmic Ray Spectrum

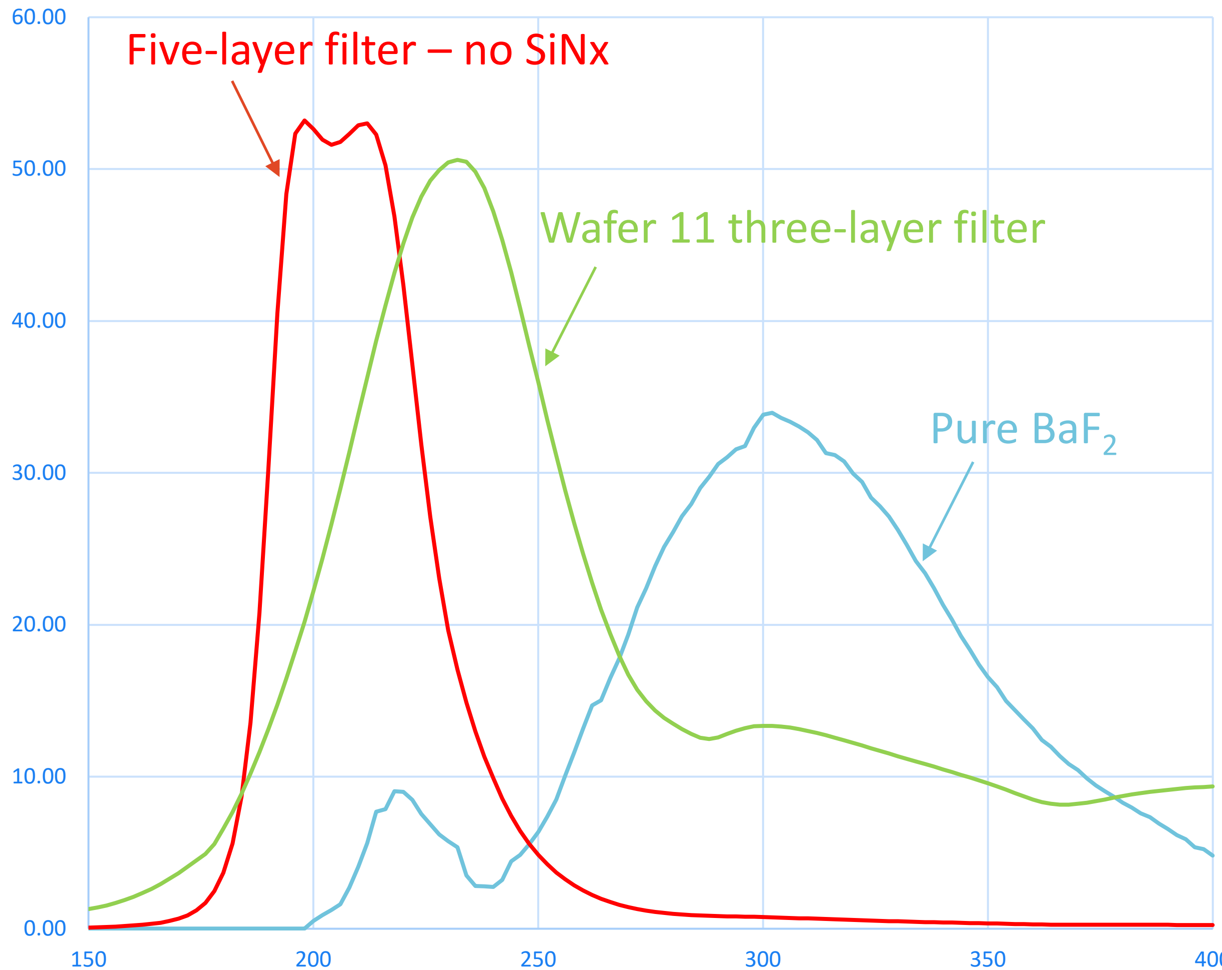


- FBK SiPM #611, dimension 6x6 mm, operated at 29.5V
- BaF_2 dimension 1” x 1” x 1”, wrapped with teflon with an opening of 6x6 (mm)
- Cosmic ray deposits 6.374 MeV/cm * 2.54 cm = 16.2 MeV
- (26631 - 68) adc / 148 pe/adc = 180 pe
- 180 pe / 16.2 MeV = 11 pe/MeV   With 2x3 array, expect 60-70 pe/MeV

Five-layer filter design – calculation

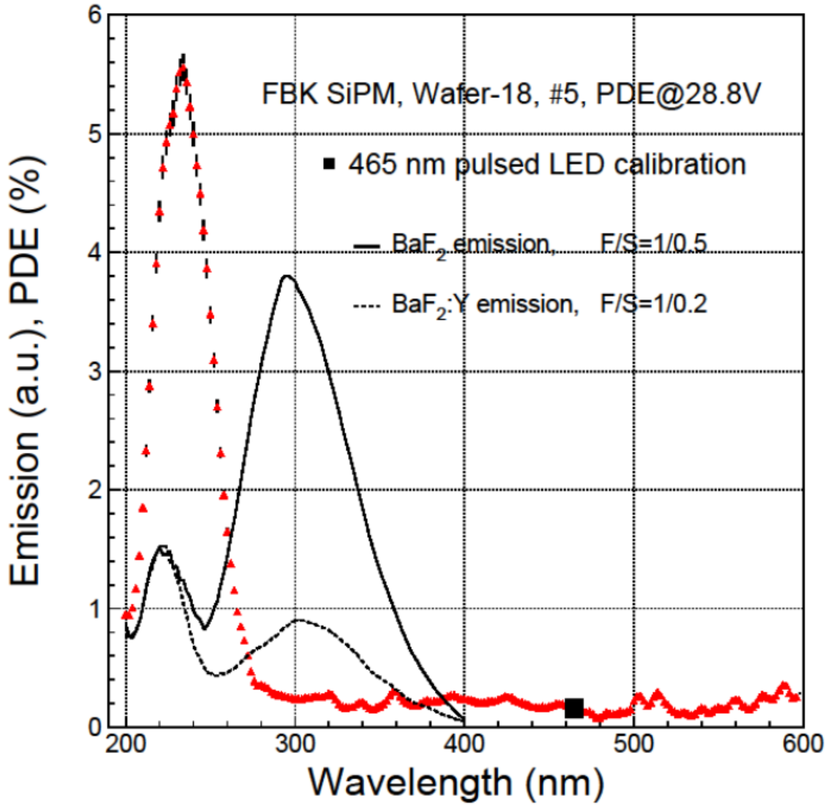
- The bandpass of the five-layer filter (this design assumes complete removal of SiNx passivation) is narrower, encompasses the small 195nm fast component and has superior suppression of the slow component





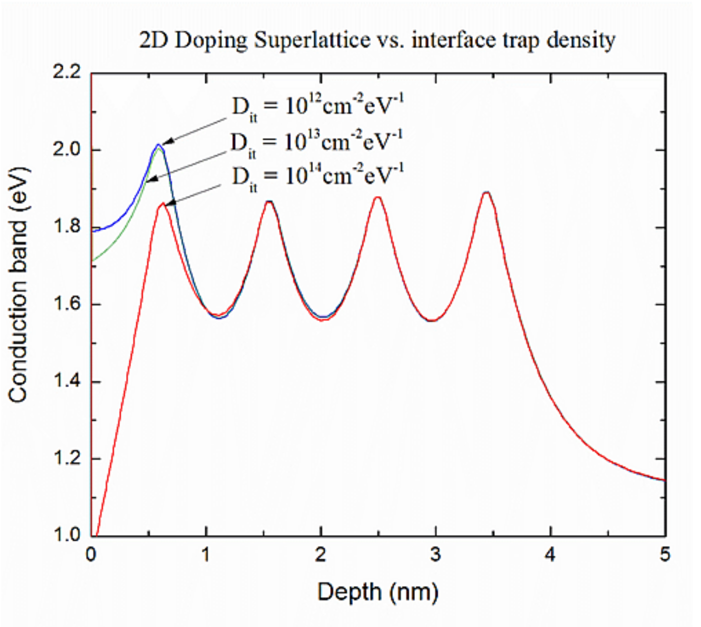
Integrated five-layer filter on an FBK SiPM

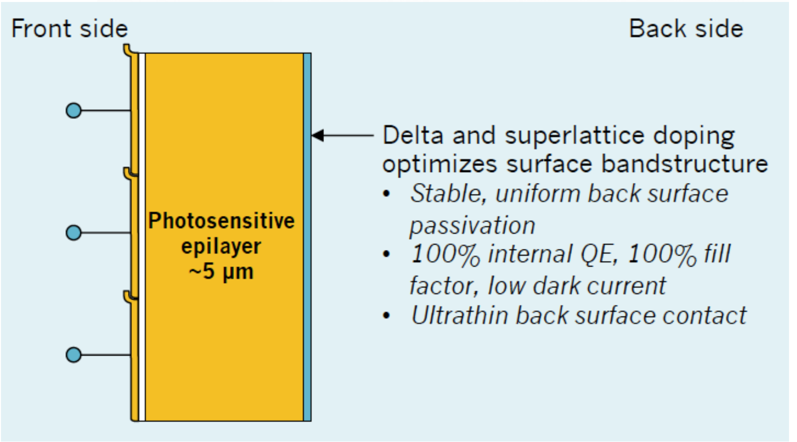
- PDE of a five-layer filter SiPM
- The good news
  - Better centering on fast component
  - Better suppression of slow component
- The bad news
  - Higher leakage current $\Rightarrow$ more noise
  - Lower PDE at peak
- Running at lower temperature can improve leakage current and PDE
- A new wafer with different initial passivation has been fabricated and delivered to JPL last week for application of another five-layer filter
- We expect the same or better bandpass performance and high PDE



Superlattice structures

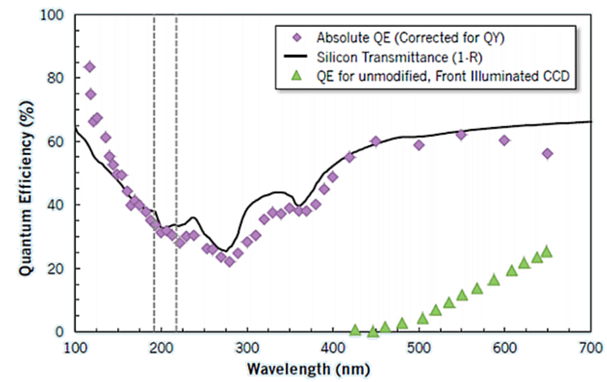
- JPL has developed superlattice (delta-doped) structures that provide enhanced quantum efficiency and improved time response for photosensors
  - Delta-doped superlattices have been successfully employed for many years to enhance the UV performance of CCDs and APDs used in UV astronomy in satellites 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



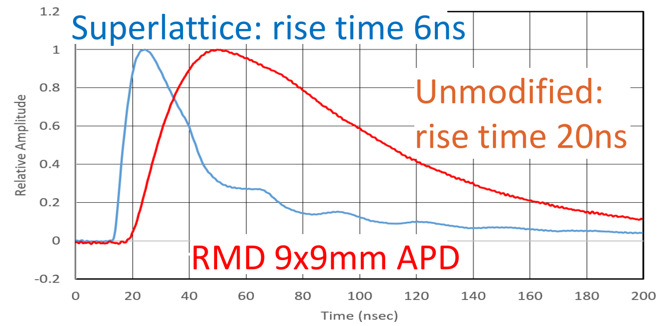


What does the superlattice do?

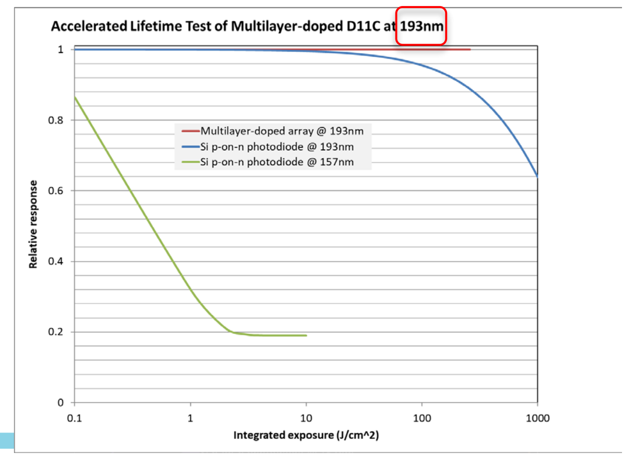
- Recombination of photoelectrons is suppressed by quantum exclusion, resulting in close to **100% internal QE**
  - Quantum efficiency in the 200-300 nm region approaches the silicon transmittance (1-R) limit



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



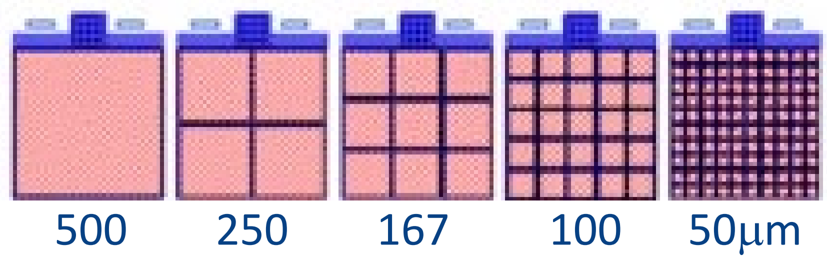
- The superlattice structure provides **stability under intense UV illumination**
  - Relevant regime for Mu2e-II is ~ .1-10 J/cm^2 of 200 -300 nm UV (~ 4-6 eV)



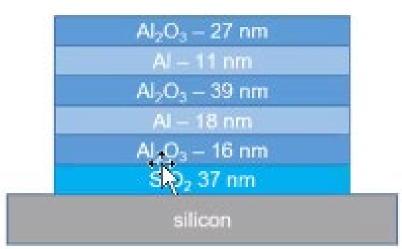
U. Arp *et al.*, J. Elect. Spect. and Related Phenomena, **144**, 1039 (2005)

Next steps in the program

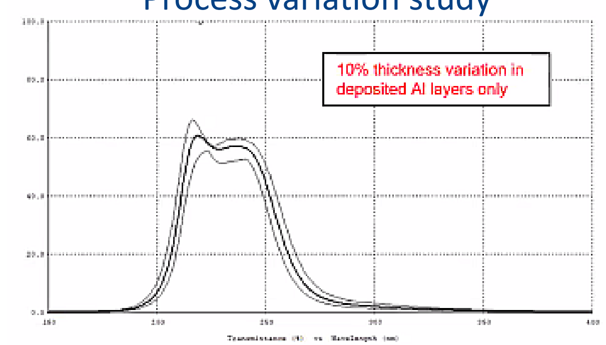
1. **Optimization of the MBE superlattice layer parameters**
   - In order to decouple the details of fabricating surface structures from the avalanche structures, this will first be done on a photodiode (*i.e.,* no gain)
   - A superlattice will be added to diode structures with SiPM-like layouts of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



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



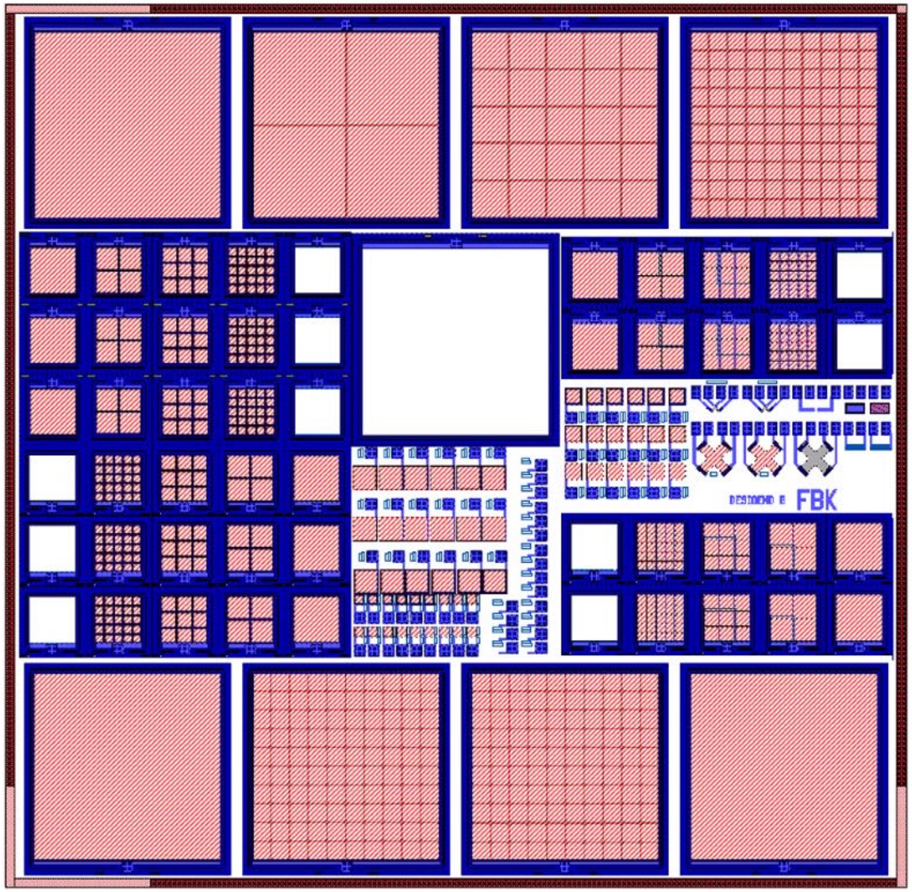
Process variation study



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



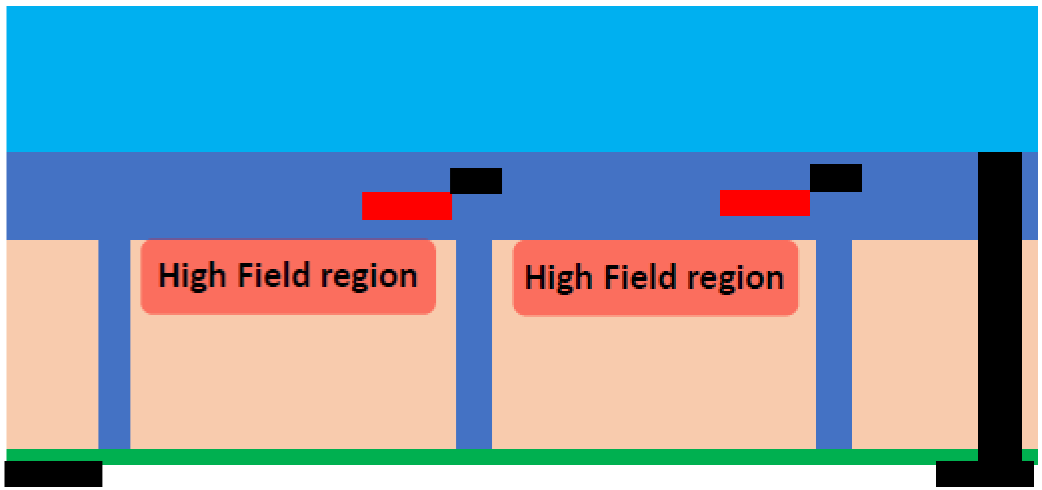
Shot size ~10x10mm^2

2

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

- **Awaits funding**

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