Summary of Mu2eII Calorimeter Workshop

Mu2e-II Snowmass21 Workshop
September 23, 2020

L. Morescalchi
On behalf of the Mu2e-II Calorimeter group

Calorimeter Workshop

- The workshop had a wide participation.. thanks to all the people who contributed to the discussion! We had 7 talks:

Introduction and overview
Speaker: Dr Ivano Sarra (LNF - INFN)

→ Introduction in term of requirements: the baseline solution is to use BaF2 crystals

Doping of barium fluoride
Speaker: Ren-yuan Zhu (Caltech)

Measurements of doped BaF2 crystals
Speaker: Yuri Davydov (JINR)

→ R&D work on BaF2: efforts to reduce the slow component acting on rare earth doping and radiation hardness measurement

SiPM for the fast component of BaF2
Speaker: David Hitlin (Caltech)

Sensors with nanoparticle filters
Speaker: Stephen Magill (Argonne National Laboratory)

Solar blind MCP
Speaker: Nikolay Atanov

→ R&D work on photosensors: efforts to find a viable strategy to develop new UV extended - solar blind photosensors

Next generation calorimeter DAQ
Speaker: Franco Spinella

→ Some ideas on a new strategy for the Mu2e-II calorimeter DAQ

Introduction and Overview

Ivano's Talk

- Let's summarize the calorimeter scope in Mu2e/Mu2e-II experiment:

1. work as an independent trigger for the experiment:
   - a good energy resolution is needed → lower than 10% from 50 MeV
2. Seed for the tracker reconstruction and provide a good T0
   - good time resolution is needed → lower than 500 ps from 50 MeV
3. PID
   - Good energy and time resolutions (10% and 500 ps)
4. Provide independent (from STM) muon stop normalization
   - With dedicated LYSO or LaBr crystals

- What is changing is the beam intensity.. So we have tighter requirements in the radiation hardness of the components and in the capacity to solve pileup

Radiation Hardness Requirements

Ivano's Talk

- These are the expected values for TID on the crystals of both disks:

X 10 Factor →

Disk1:
Inner:(60x 5 x 3 → 900 krad
Outer:((15x5x3) → 180 krad

Disk2:
Inner: (10x 5 x 3) → 150krad
Outer:(5x5x3) → 75 krad

- These are the expected values for TID and neutron fluence on the photosensors:

X 10 Factor →

Disk1: Inner:
(10x2x 5 x 3) → 300 krad
Outer: (10x0.5x5x3) → 75 krad

Disk2:
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

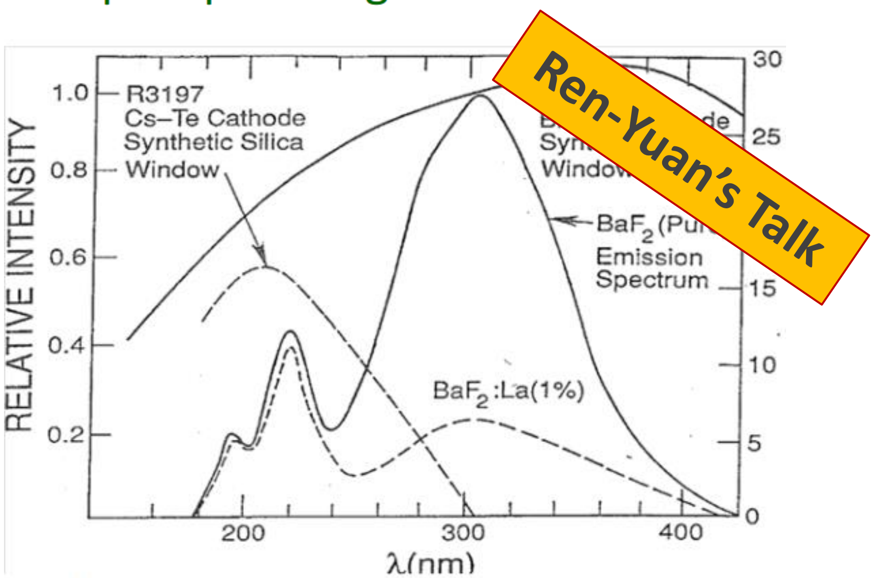
Disk 1 = $10 \times 6 \times 10^{10} \times 5 \times 3 = 900 \times 10^{10} = 9 \times 10^{12}$

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

BaF2 as Baseline Solution

- BaF_2 crystal has a ultrafast scintillation at 220 nm with 0.5 ns decay time and a similar intensity as CsI, and may survive 100 Mrad. Its slow scintillation at 300 nm with 650 ns decay time, however, causes pileup in a high rate environment.

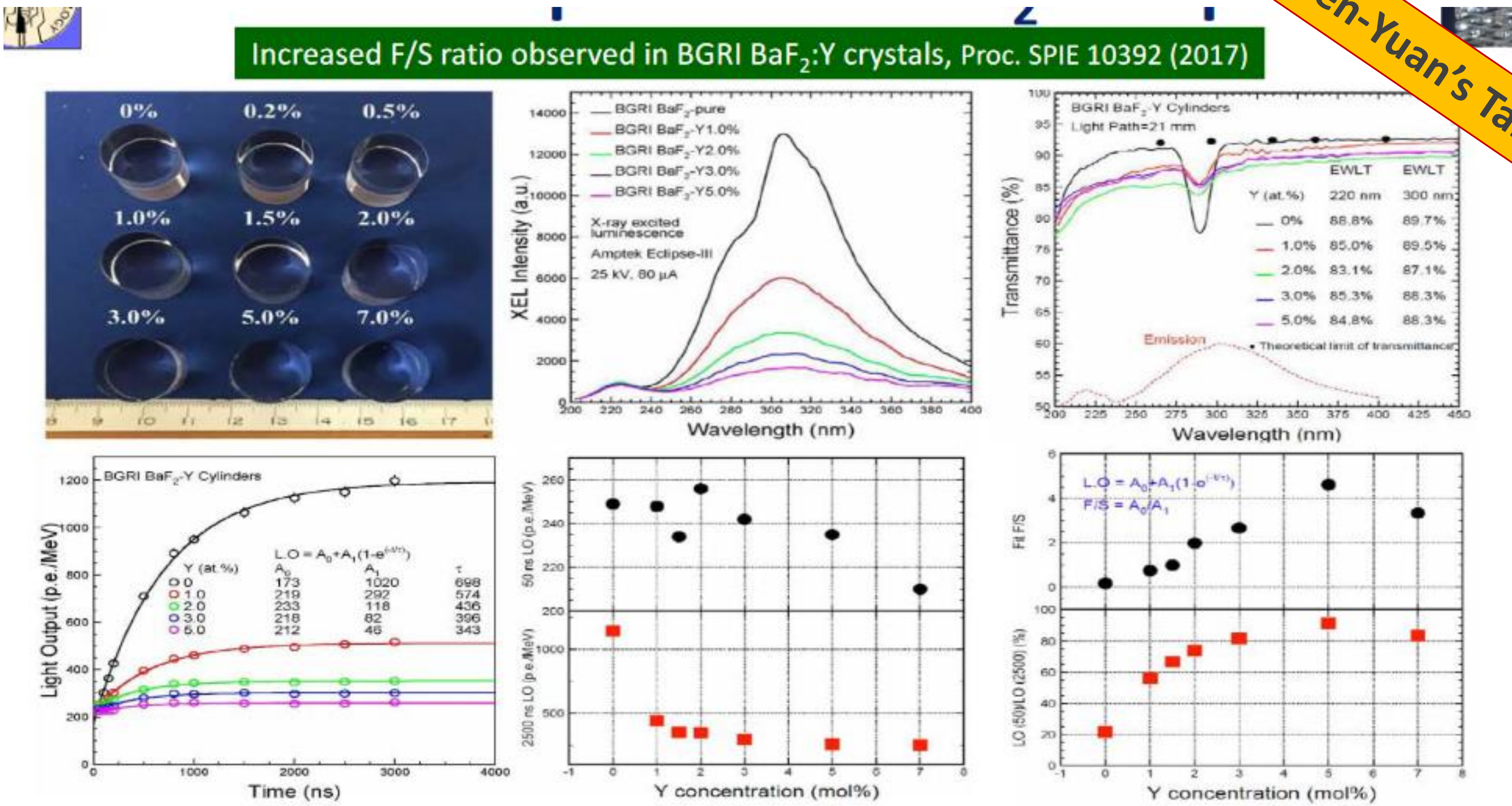
	LSO/LYSO	CsI	BaF₂
Density (g/cm³)	7.4	4.51	4.89
Melting point (°C)	2050	621	1280
Radiation Length (cm)	1.14	1.86	2.03
Molière Radius (cm)	2.07	3.57	3.1
Interaction Length (cm)	20.9	39.3	30.7
Z value	64.8	54	51.6
dE/dX (MeV/cm)	9.55	5.56	6.52
Emission Peak[a] (nm)	420	310	300 220
Refractive Index[b]	1.82	1.95	1.5
Relative Light Yield[a,c]	100	3.6 1.1	42 4.1
Decay Time[a] (ns)	40	30 6	650 0.5
d(LY)/dT [d] (%/°C)	-0.2	-1.4	-1.9 0.1



- Slow suppression may be achieved by rare earth (Y, La and Ce) doping, and/or solar-blind photo-detectors, e.g. Cs-Te , K-Cs-Te and Rb-Te cathode

Yttrium Doped Small BaF2 Samples

Ren-Yuan's Talk



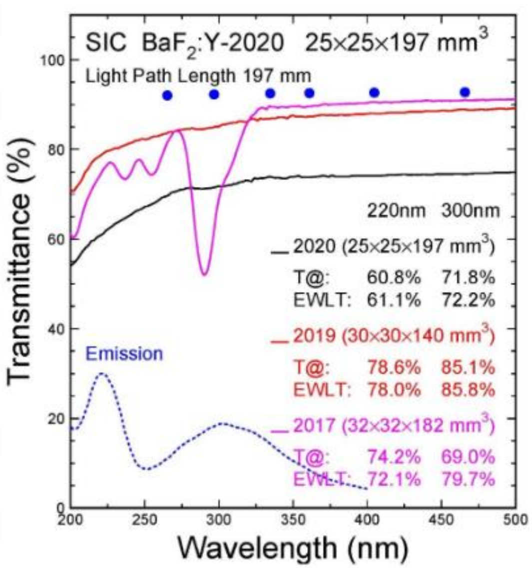
- Y doping can suppress slow scintillation component of BaF2

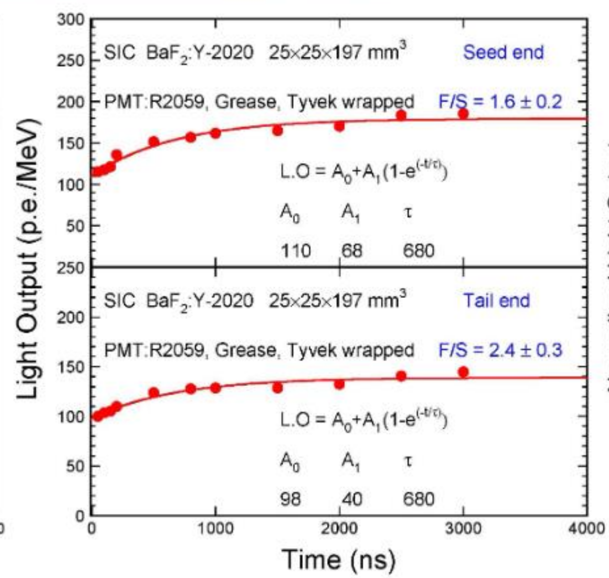
Yttrium Doped Large BaF2 Crystals

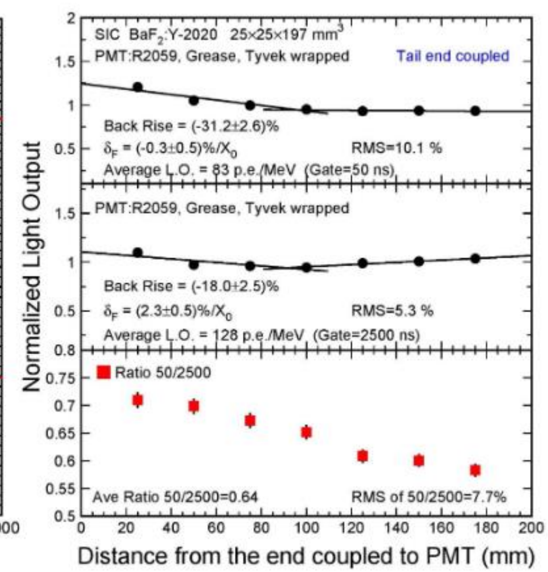
- Achievable performance of 20 cm long BaF_2:Y crystals: LO_F>100 p.e./MeV, F/S>2, <10% LRU and $|\delta_F|<3\%/X_0$. R&D will continue to optimize yttrium doping in large size BaF_2:Y crystals for Mu2e-II.

Ren-Yuan's Talk

F: 100 p.e./MeV, F/S: 2
F/T LRU: 10%/5% %, δ_F:-0.3%/X_0



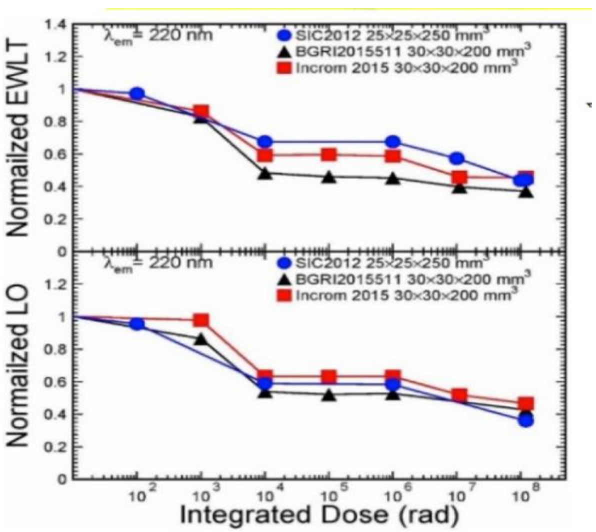


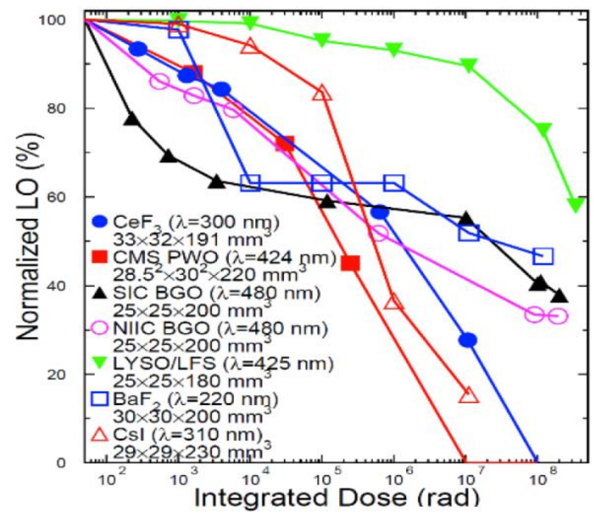


BaF2 Radiation Hardness

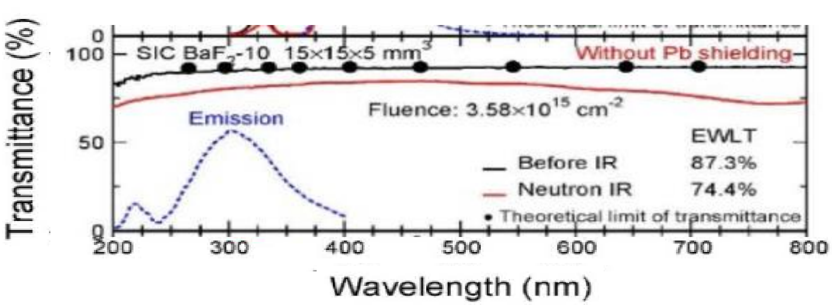
- 20 cm long BaF_2 crystals show ~50% LO loss after 120 Mrad. 5 mm thick BaF_2 plates show less than 20% LO after 1 x 10^{15} p/cm^2 or 3.6 x 10^{15} n_{eq}/cm^2, indicating that BaF_2 of short light path may be used in a severe radiation environment.

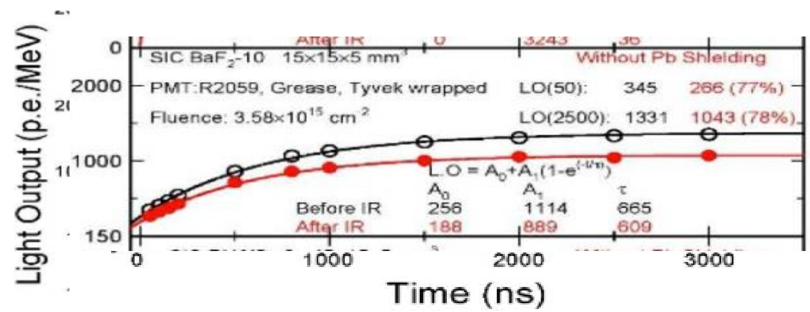
Ren-Yuan's Talk





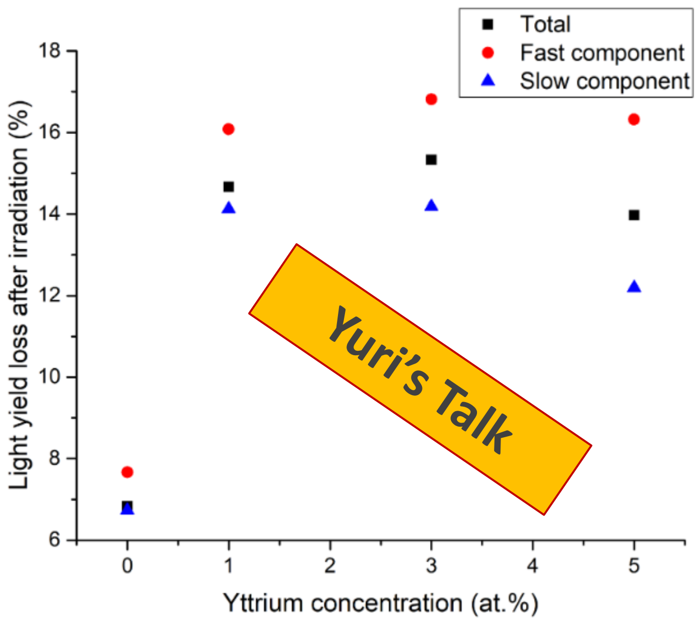
- γ-Ray Induced Damage in Large BaF2
- Neutrons induced damage





Preliminary BaF2:Y Radiation Hardness

- Four 10x10x10 mm^3 BaF2:Y samples from SICCAS with different doping concentration have been irradiated with neutrons at IBR-2M facility in Dubna
- Number of neutrons has been monitored using a nickel wire: about **2.3x10^14 n/cm^2** passed through the samples. The neutrons energy spectrum is unknown, so it's difficult to compute fluence in 1 MeVeq n



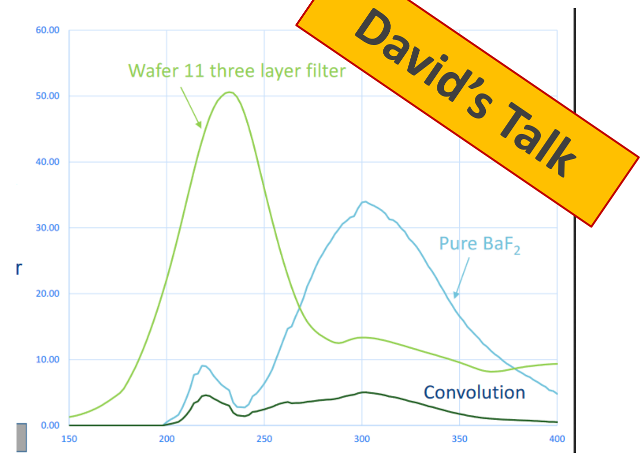
Y doping	0% (pure)	1at.%	3at.%	5at.%
Fast	7.6%	16.1%	16.8%	16.3%
Slow	6.8%	14.4	15.5	13.4
Total	6.9%	14.7%	15.3%	14.0%

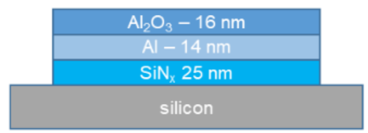
- ❑ The light yield losses after neutron irradiation are almost two times higher for the yttrium doped samples compared to the losses in the pure BaF_2 sample
- ❑ The light yield loss of the fast component after neutron irradiation is higher compared with the slow component on all samples

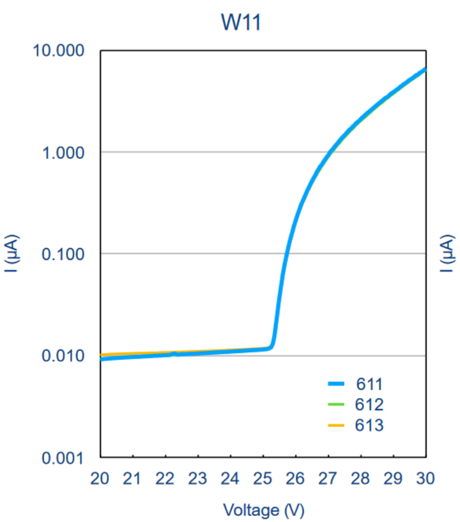
Obviously, more study is required in a wider range of radiation doses…

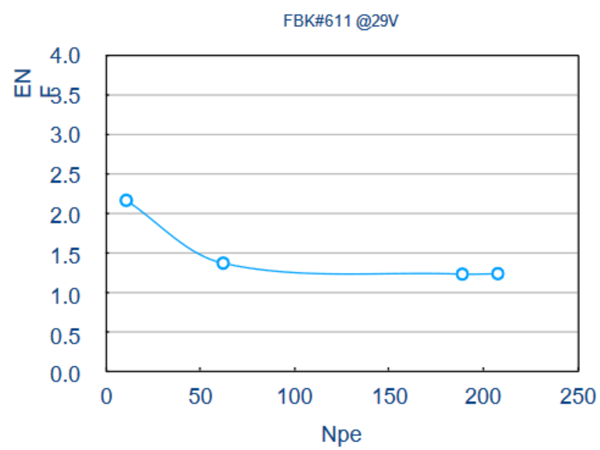
CIT/FBK/JPL Solar Blind SiPM – 3 Layers

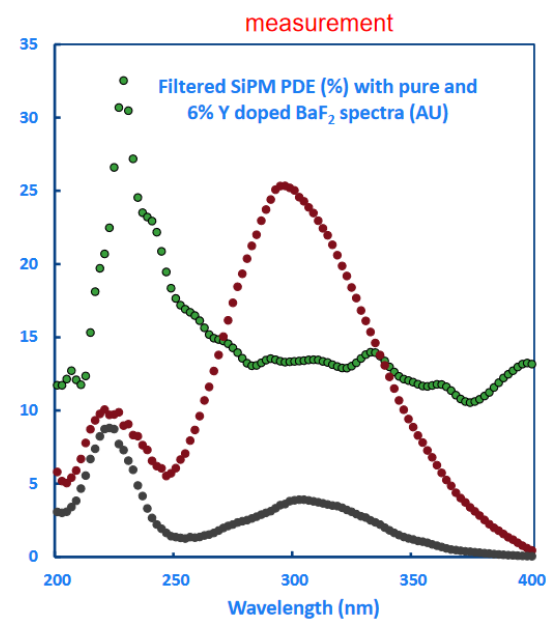
- Building on our experience with a large area APD developed with RMD, we have adopted a phased development approach
    1. Build a three layer ALD filter on a 6x6 mm NUV SiPM structure, exploring different SiNx passivation layers, guard ring structures, ……
    2. Fabricate 2x3 arrays of the 6x6 mm chips, 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





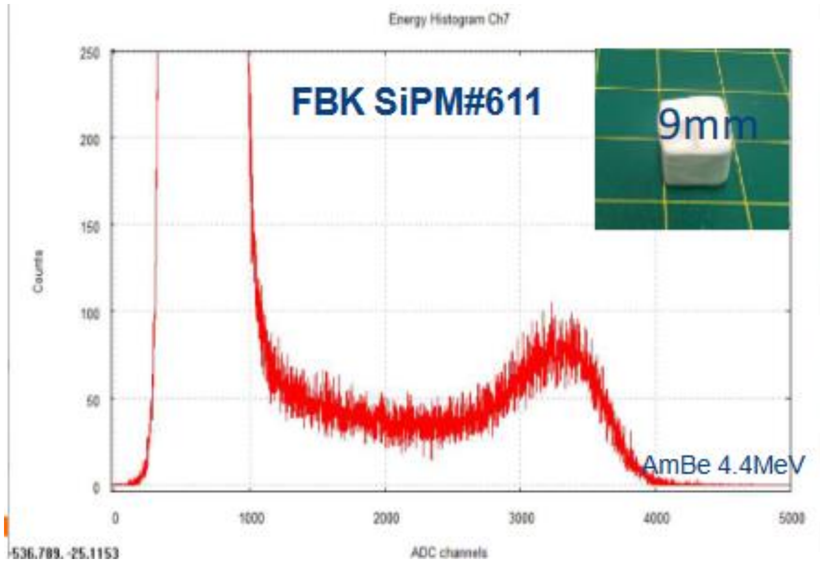






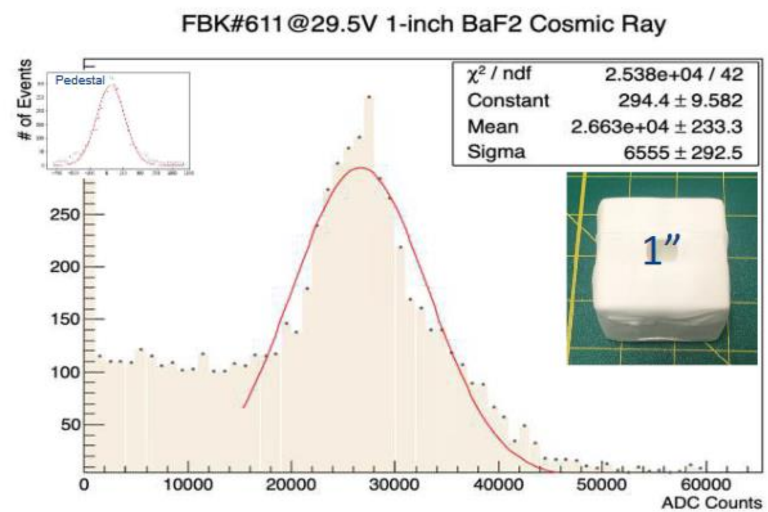
FBK #611 + BaF2: Source and Cosmic Rays

David's Talk



- 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

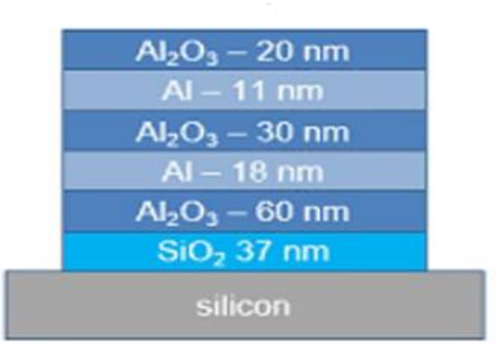
- FBK SiPM #611, dimension 6x6 mm, operated at 29.5V
- BaF2 dimension 1” x 1” x 1”, wrapped with teflon with an opening of 6x6 (mm)
- Cosmic ray deposits 6.374 MeV/cm * 2.54 cm = 16.2MeV -> 11pe/MeV
- With 2x3 array are expected 60-70 pe/MeV

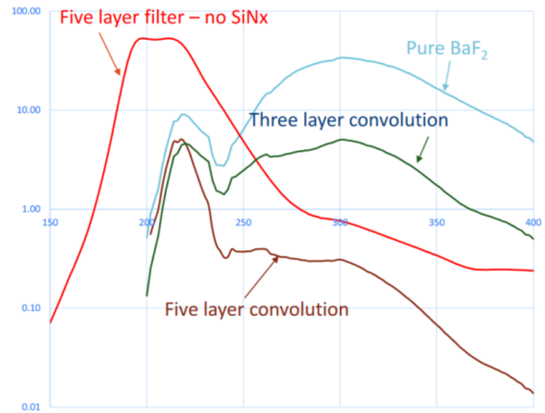


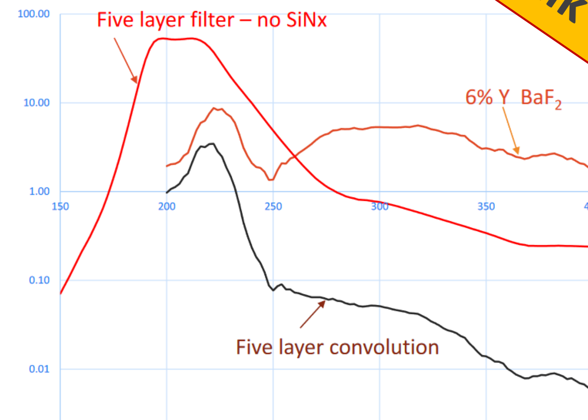
Future Plans for Solar Blind SiPMs

David's Talk

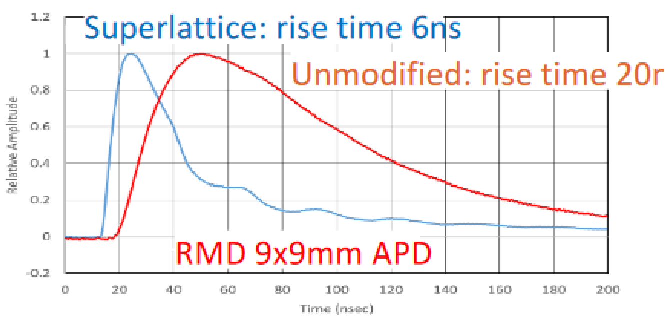
- A 5 layer filter has been developed with performance adequate for Mu2e-II:

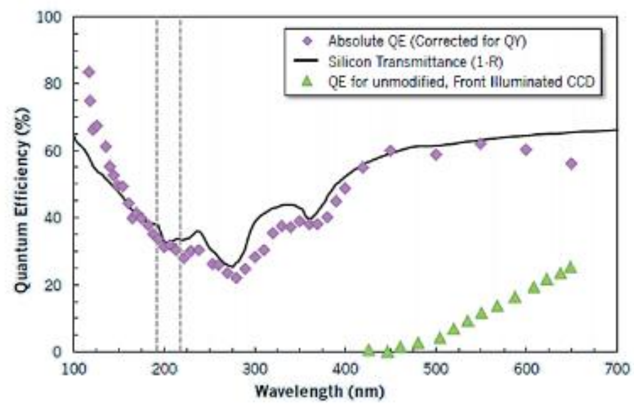




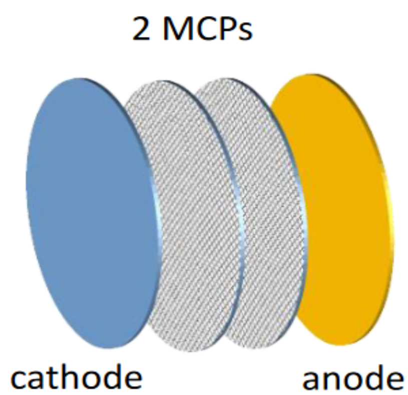


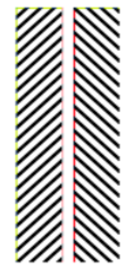
- It can be implemented in a delta-doped, back illuminated version that will have improved QE and timing characteristics:



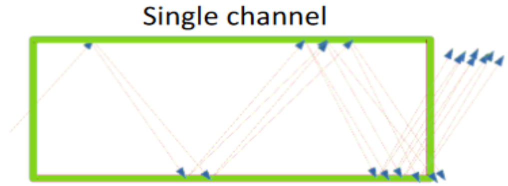


AlGaN Photocathodes in MCP



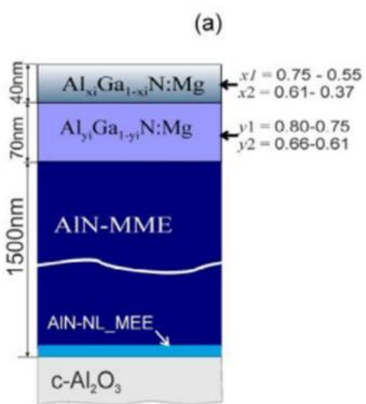


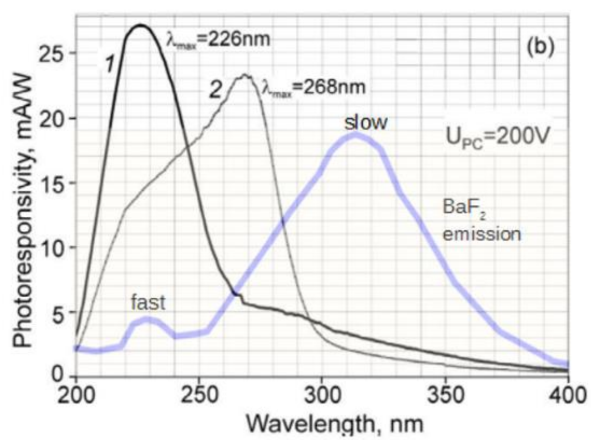
- gain 10^6

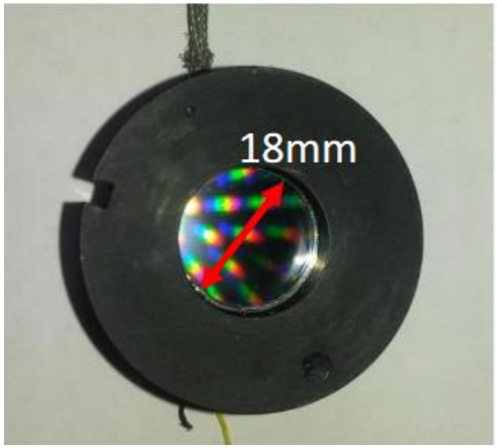


Nikolay's Talk

AlGaN cathodes with cut at 260 and 280 nm were assembled with 2 MCPs and anode in metal package to produce device which has 18 mm input window.

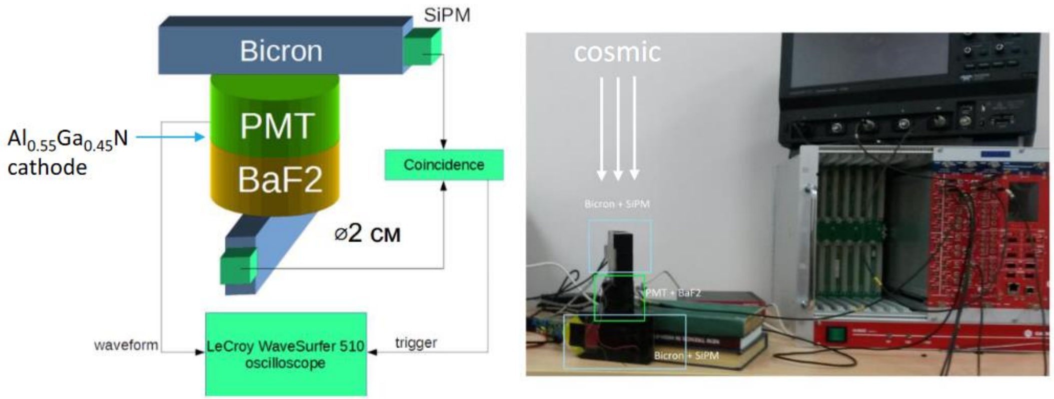






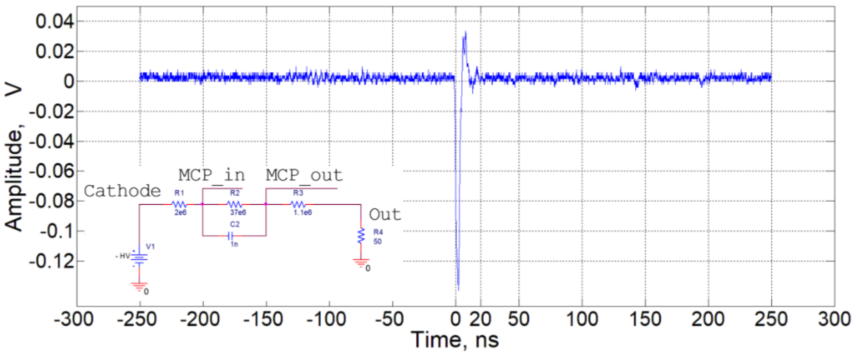
AlGaN MCP – Cosmic Rays Test

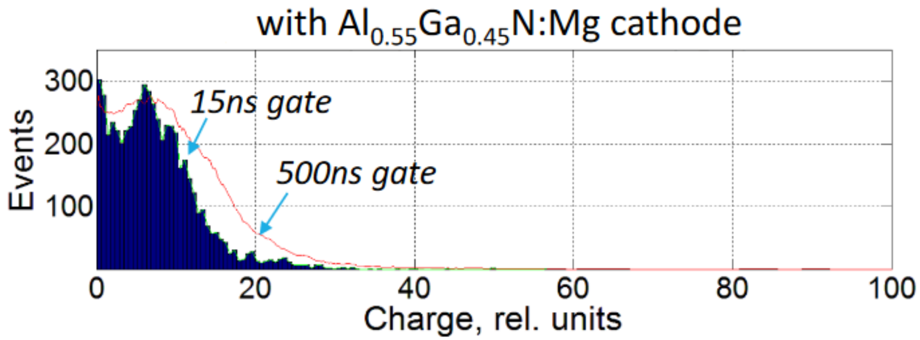
Nikolay's Talk



Experimental setup to measure energy losses spectrum for zenith cosmic rays.

Typical response of BaF_2 + MCP device with $Al_{0.55}Ga_{0.45}N$:Mg cathode for zenith cosmic rays. One can see sharp fast component response, and slow component signal for time less than 20 ns goes to noise level.

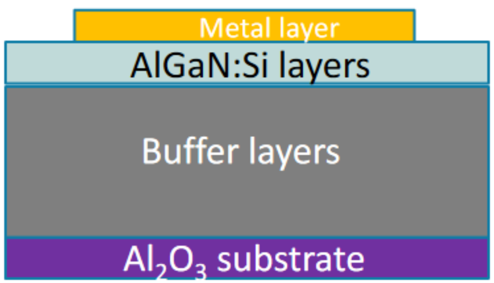




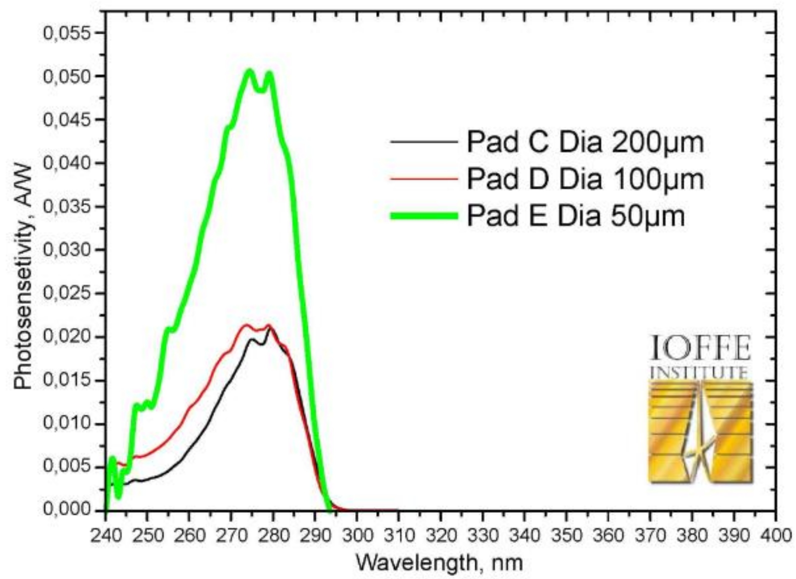
AlGaN Schottky Diode

- AlGaN Schottky barrier photodiode for BaF_2 fast component selection is proposed

Nikolay's Talk



Dark current ~0.5 uA at -5V
QE is 22% @ 280nm



We can use AlGaN to grow structure for Schottky photodiode. At the moment we have photodiodes with 50 mA/W sensitivity for Vbias = 0

Sensors with nanoparticle filters

Steve's Talk

Quantum Confinement changes material properties when particle size < electron wavelength

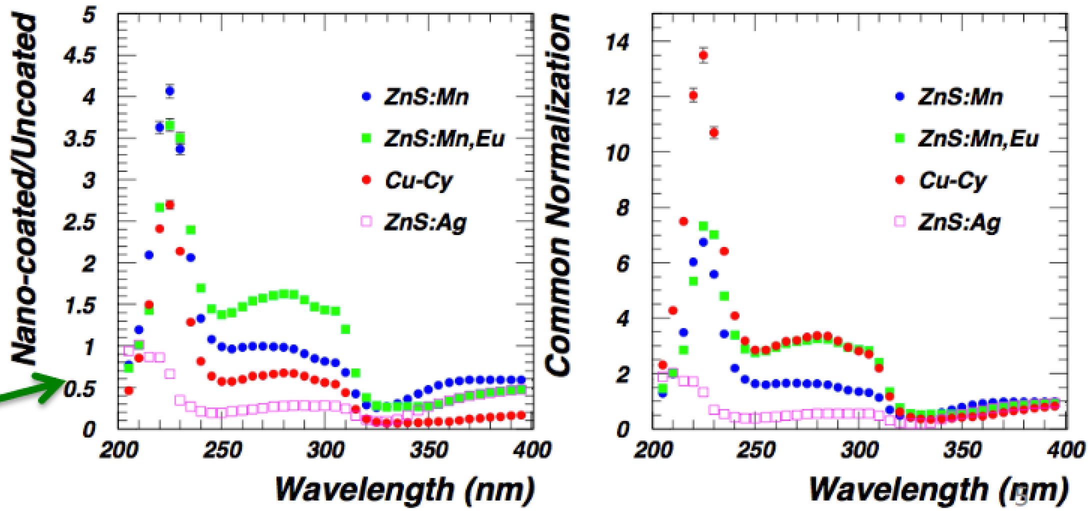
Eg increases with decreasing particle size -> ***UV photon absorption***

Stokes Shift is difference between absorption and emission wavelength

Nanoparticles deposited on clear plastic tape (UTA partner)

Published result:
SR 8:10515 (2018)

Enhanced response for ¾ samples:
200 nm < λ < 250 nm



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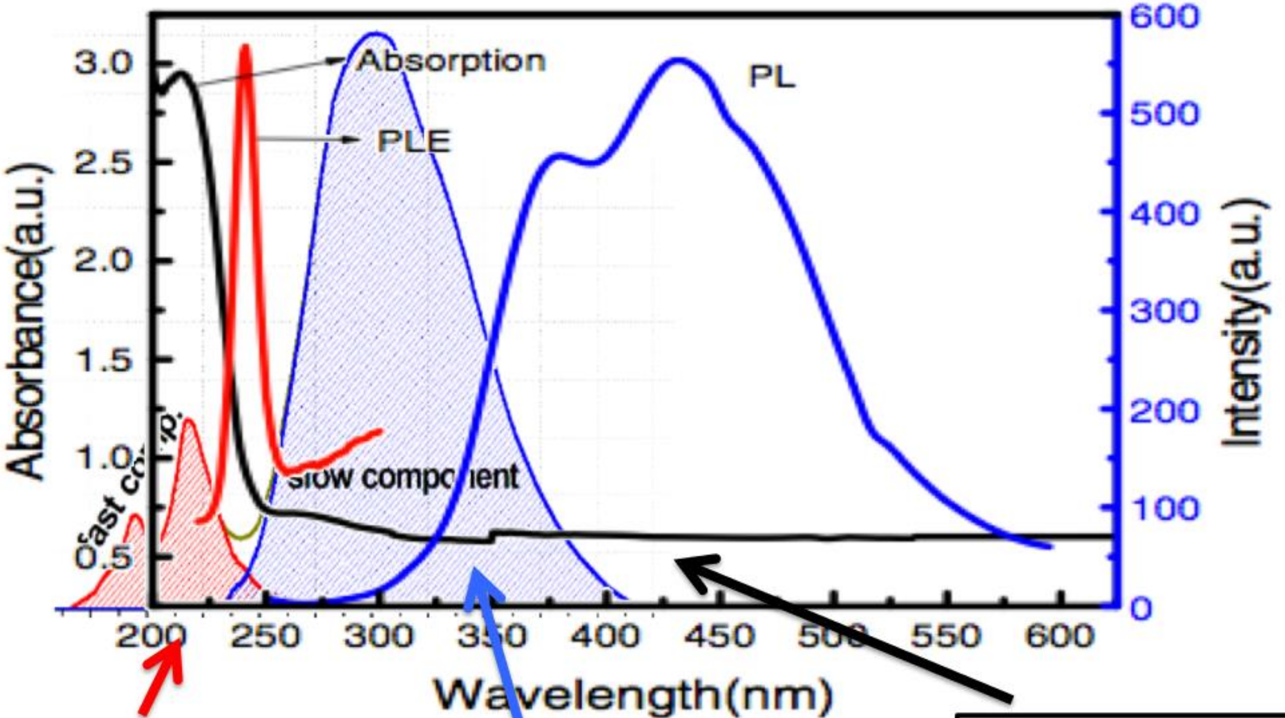
Sensors with nanoparticle filters

Steve's Talk



195, 224 nm emission of BaF2
absorption peak of nanoparticle

Little absorption for wavelengths >250 nm

Overlap of slow component and nanoparticle emission:
1) wave-shift to longer wavelength, or 2) resin coating on the SiPM

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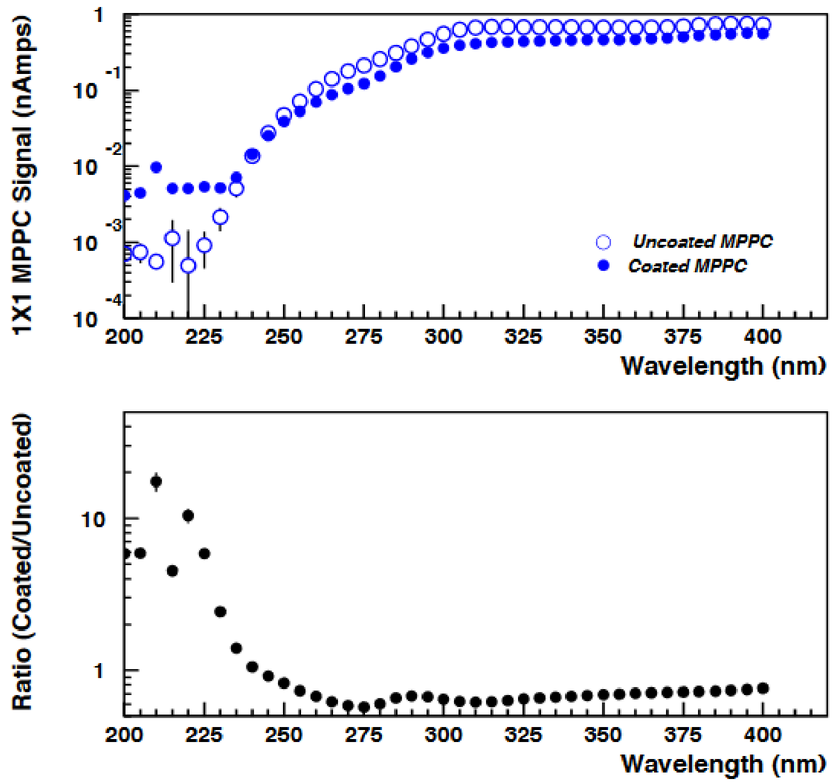
Perspective for Nanoparticles and BaF2

Steve's Talk



UTA nanoparticles *deposited directly on the resin (face) of the SiPM*

Enhanced response of coated SiPM seen in the wavelength range from 200 nm – 240 nm compared to uncoated sensor

Without any optimization, ratio of coated to uncoated in the 200 – 240 nm range is ~factor of 10 greater than in the region > 250 nm!

We have tested at least 2 nanoparticle candidates which show sensitivity in the desired wavelength range and, in addition, much reduced sensitivity without the need for additional filters in the wavelength range > 250 nm

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Next Generation Calorimeter DAQ

- Current readout scheme (200 MHz ADCs) is not ok for Mu2e II: we expect more (x3) signals with a length o(30 nsec) and a rise time o(5 nsec)

→
- ❑ Ultra Fast ADC (1 GHz ...)
- ❑ TDC
- ❑ TDC + ADC

?

Franco's Talk

- Radiation Hardness requirements for electronics increases up to **o(1Mrad) !!**
  - ➢ Only Xilinx Virtex5-QV FPGA, that space grade qualified, meets this requirement in 2020
  - ➢ ADC need to be qualified, while TDC chip has been qualified by CERN

1. Ultra Fast ADC

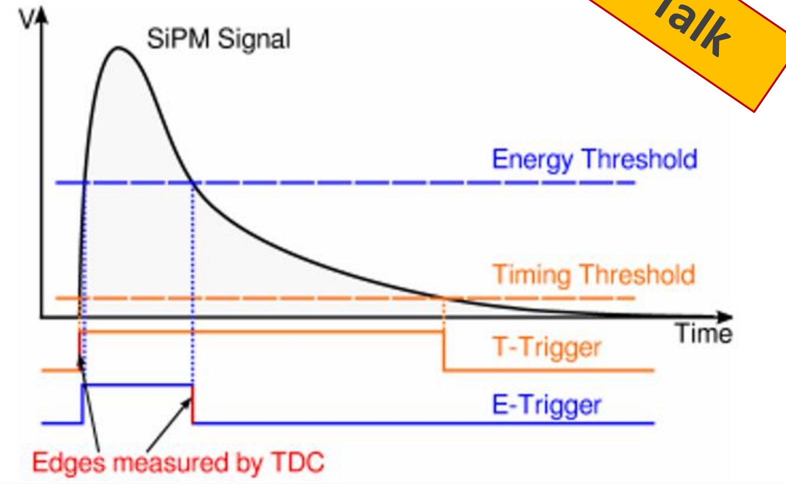
- Ultra Fast ADCs (1 GHz) would solve the pileup issue, but bandwidth would increase
- Ultra Fast ADCs are expensive (400 $/unit), power hungry and each needs 4 JESD 204 FPGA serializers
  - ➢ A 20 channels board would consume 60-100 W and would need 40 serializers to handle ADCs data, so the number of FPGA/board will increase to 3
- Calculating parameters in real-time and/or developing a a L0 trigger system can help to save bandwidth and storage room

Next Generation Calorimeter DAQ

Franco's Talk

2. TDC

- TDCs offer a very good time resolution and a good energy resolution is signal shape is stable
- **TDCs don't solve the pileup easily**
- CERN developed picoTDC, a new cheap RadHard 64 channels TDC chip with a 3 ps reaolution
- There is also a discriminator chip from CERN: FastIC



3. TDC + Slow ADC

- To solve pile-up problem we could use a TDC (PicoTDC) + a relatively slow ADC
- How much slow ? If signals o(30 nsec) 100 or 200 Msamples should be ok.
- We could still try to fuse TDC and ADC data on the flight and directly send hit parameters to DAQ ...

- We will need a lot of simulations and laboratory R&D to choose the best solution in terms of performance and cost ...

Considerations

<u>List of R&D tests for whatever proposed solution</u>

→ Measure resistance to doses

→ Measure resistance to neutrons up to 10^{13} n_1MeV/cm^2

→ Control behavior at low temperatures

→ Measure resistance for large integrated charge