CALORIMETER SESSION: Summary

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Workshop on a Future Muon Program At Fermilab @ Caltech
March 29, 2023

Calorimeter Session

We had 6 talks:

- Introduction to Mu2e-II in term of requirements.

- Baseline solution is to use BaF2 crystals
  → efforts to reduce the slow component working on

  Crystals — Photo-sensors

- Radiation Hardness on Crystals

- Alternative solution

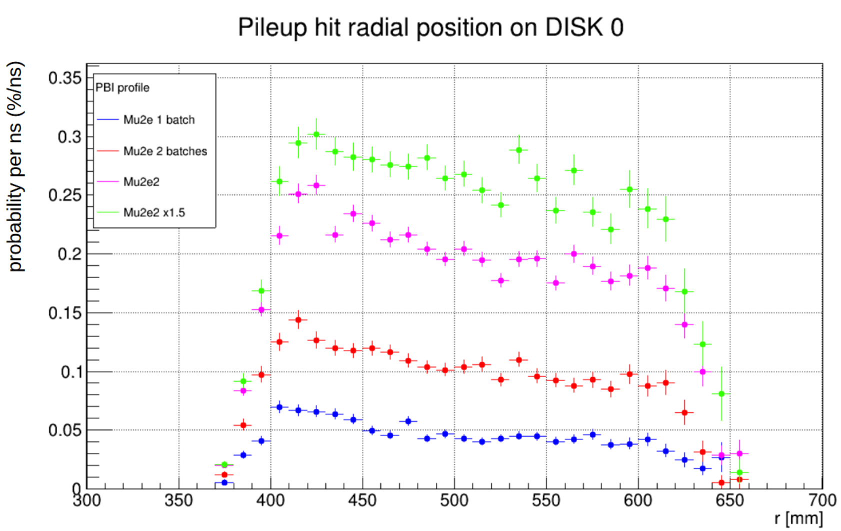
Calorimeter Requirements (1/3)

Luca's talk

Maintain the Mu2e-I requirement:

- We aim to same energy (< 10%) and time (< 500 ps) resolutions as in Mu2e.
- Aiming to provide standalone trigger, track seeding and PID as before.
- Work in vacuum @ 10^{-4} Torr, keep a low level of outgassing.

Face up to the higher rate, neutron fux and dose **on Disks**:



- **The pileup with respect to CE seems to scale linearly with beam intensity**, so to keep the same level we have in Mu2e (15%) with 150 ns we need to rescale the new signals lenght:

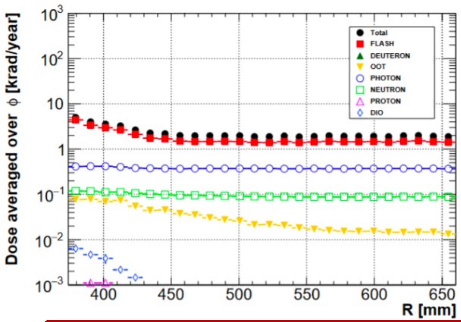
1. The length for Mu2e-II should be 75 ns (50 ns for 1.5 times Mu2e-II)

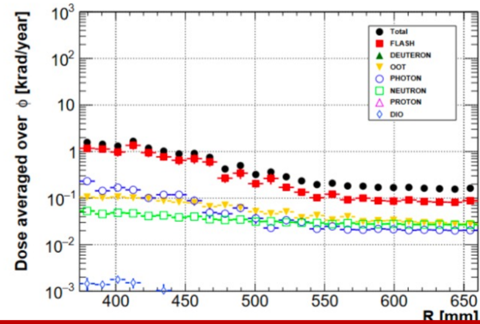
Pileup resolution in the waveform fit is still under study and can loose this requirement

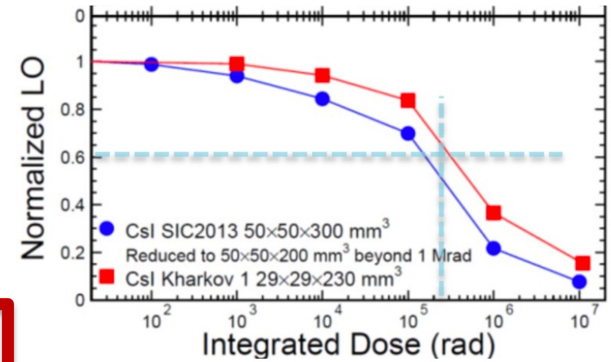
Calorimeter Requirements (2/3)

Luca's talk

- Under the **assumption** that the TID from the beam flash in the calorimeter from 800 MeV protons scales as the number of stopped muons wrt Mu2e 8 GeV beam, a **x10** is expected:



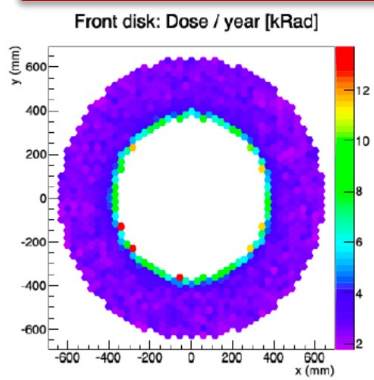




F. Yang, L. Zhang and R. -Y. Zhu, "Gamma-Ray Induced Radiation Damage Up to 340 Mrad in Various Scintillation Crystals," in *IEEE Transactions on Nuclear Science*, vol. 63, no. 2, pp. 612-619, April 2016, doi: 10.1109/TNS.2015.2505721.

TID req = simulated TID x3 Safety Factor, x3 yrs, x10 Mu2-II

- R < 47 cm -> **600 krad**	- R < 55 cm -> **160 krad**
- R > 47 cm -> **180 krad**	- R > 52 cm -> **50 krad**

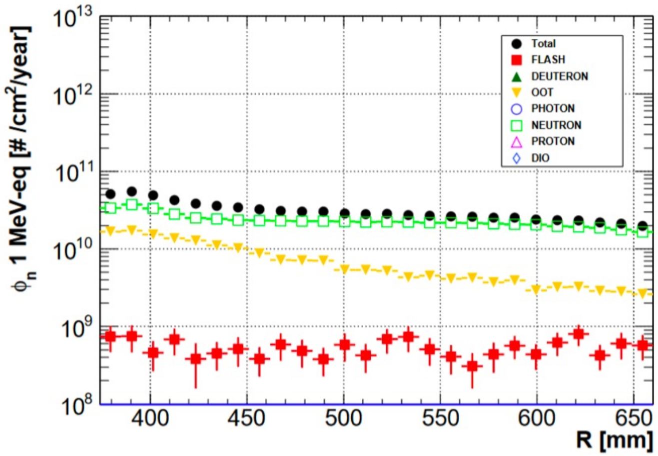


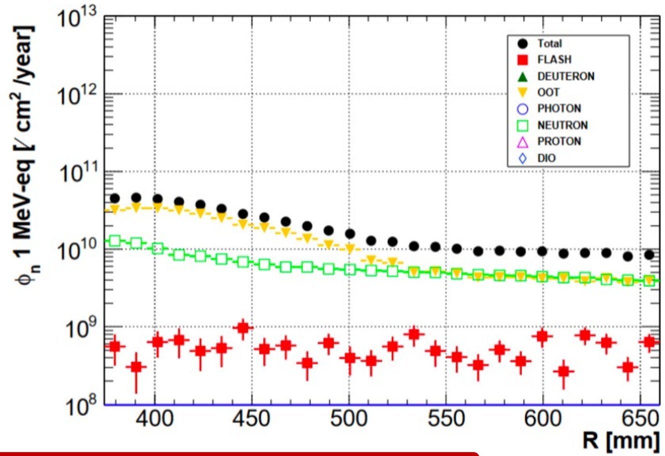
- Mu2e QA requirement for TID was a **LO after 100 krad > 60%**
  - The requirements on light collection was 30 p.e./MeV
- Dedicated simulation of the new beam flash and upgraded detectors materials are required to determine exact numbers, but so far wrt TID:
  - Disk 1 crystals should survive the new radiation level (??)
  - Disk 0 outer crystals should be in the same situation of disk 1 inner (??)
  - **Disk 0 inner crystals must be changed** -> BaF2, LYSO (??)

Calorimeter Requirements (3/3)

Luca's talk

- Neutrons comes mainly from muonic atom decays, so a **x10 factor** wrt Mu2e is expected





1MeV-eq n Fluence = simulated Fluence x3 Safety Factor, x3 yrs, x10 Mu2-II

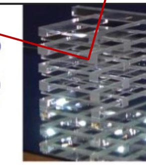
5.4 X 10^12 n/cm^2

- The **dark current value after the neutron damage** is expected to be of the order of tens of mA, mitigable (??) with decrease of breakdown voltage or lowering the operational temperature (-40 C?)
  - We need to substitute the majority (or all) the photosensors -> more rad hard sipm? solar blind?
- Other than the dark current increase related to neutrons we need also to consider the new Radiation Induced Noise (RIN) level

Crystals (1/3)

Ren-Yuan's talk

Fast/Ultrafast for HEP TOF & X-ray Imaging



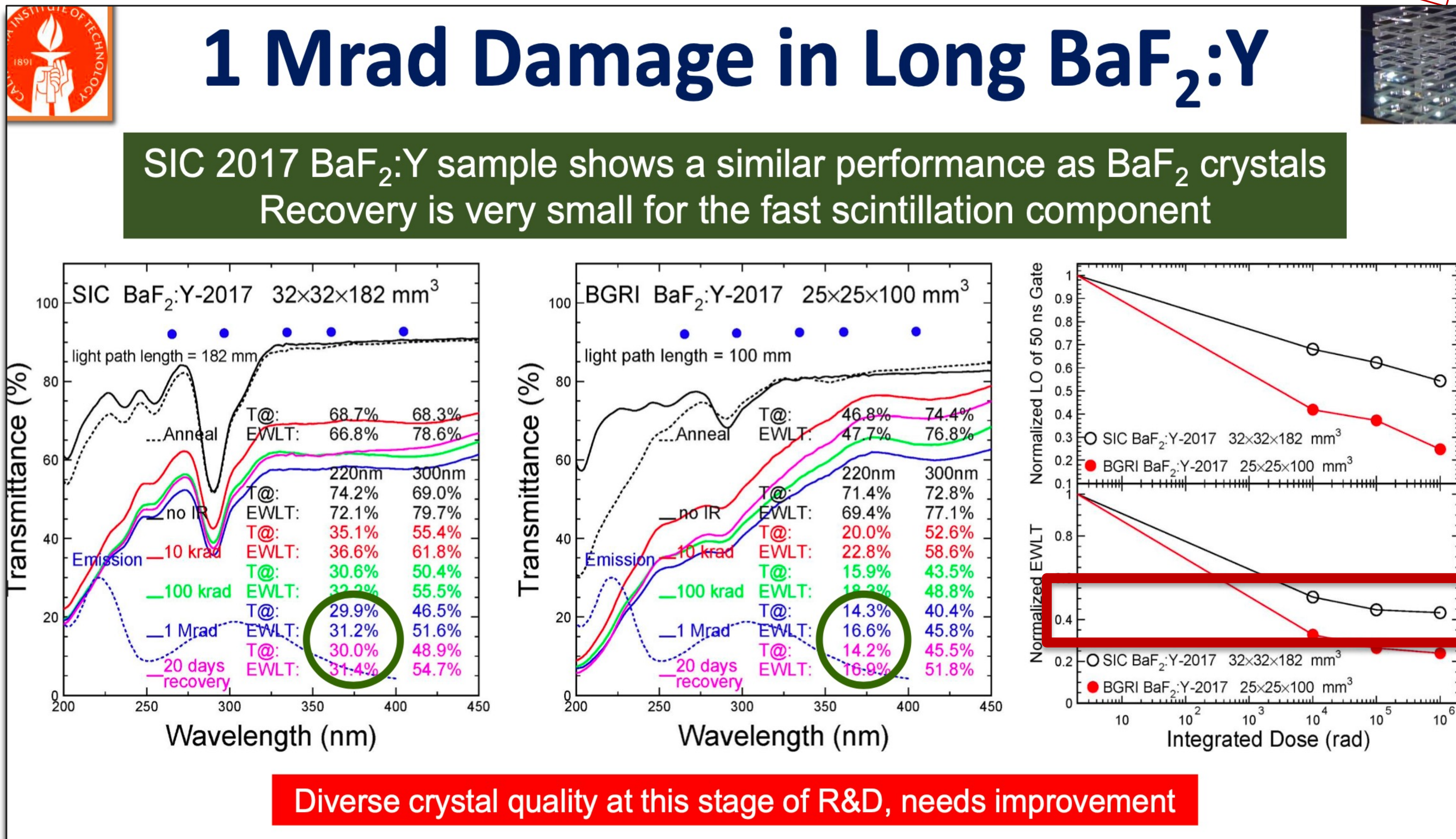
arXiv: 2203.06788

	BaF_2	BaF_2:Y	Lu_2O_3:Yb	YAP:Yb	YAG:Yb	ZnO:Ga	β-Ga_2O_3	LYSO:Ce	LuAG:Ce	YAP:Ce	GAGG:Ce	LuYAP:Ce	YSO:Ce
Density (g/cm^3)	4.89	4.89	9.42	5.35	4.56	5.67	5.94	7.4	6.76	5.35	6.5	7.2[f]	4.44
Melting points (°C)	1280	1280	2490	1870	1940	1975	1725	2050	2060	1870	1850	1930	2070
X_0 (cm)	2.03	2.03	0.81	2.59	3.53	2.51	2.51	1.14	1.45	2.59	1.63	1.37	3.10
R_M (cm)	3.1	3.1	1.72	2.45	2.76	2.28	2.20	2.07	2.15	2.45	2.20	2.01	2.93
λ_I (cm)	30.7	30.7	18.1	23.1	25.2	22.2	20.9	20.9	20.6	23.1	21.5	19.5	27.8
Z_{eff}	51.0	51.0	67.3	32.8	29.3	27.7	27.8	63.7	58.7	32.8	50.6	57.1	32.8
dE/dX (MeV/cm)	6.52	6.52	11.6	7.91	7.01	8.34	8.82	9.55	9.22	7.91	8.96	9.82	6.57
λ_{peak}[a] (nm)	300 220	300 220	370	350	350	380	380	420	520	370	540	385	420
Refractive Index[b]	1.50	1.50	2.0	1.96	1.87	2.1	1.97	1.82	1.84	1.96	1.92	1.94	1.78
Normalized Light Yield[a,c]	42 4.8	1.7 4.8	0.95	0.19[d]	0.36[d]	2.6[d] 4.0[d]	6.5 0.5	100	35[e] 48[e]	9 32	190	16 15	80
Total Light yield (ph/MeV)	13,000	2,000	280	57[d]	110[d]	2,000[d]	2,100	30,000	25,000[e]	12,000	58,000	10,000	24,000
Decay time[a] (ns)	600 0.5	600 0.5	1.1[d]	1.1[d]	1.8[d]	3.0[d] 1.0[d]	110 5.3	40	820 50	191 25	570 130	1485 36	75
LY in 1st ns (photons/MeV)	1200	1200	170	34[d]	46[d]	980[d]	43	740	240	391	400	125	318
LY in 1st ns /Total LY (%)	9.0	64	60	60	43	49	2.0	2.5	1.2	3.3	0.7	1.4	1.3
40 keV Att. Leng. (1/e, mm)	0.106	0.106	0.127	0.314	0.439	0.407	0.394	0.185	0.251	0.314	0.319	0.214	0.334

[a] top/bottom row: slow/fast component; [b] at the emission peak; [c] normalized to LYSO:Ce; [d] excited by Alpha particles; [e] 0.3 Mg at% co-doping; [f] $Lu_{0.7}Y_{0.3}AlO_3$:Ce.

Crystals (2/3)

Ren-Yuan's talk



Crystals (3/3)

Ren-Yuan's talk

SIC Mass-Produced Crystals (Mar 2019)

Scaling to X_0, order of crystal cost: PWO, BGO, CsI, BSO, BaF_2:Y, LYSO

Item	Size	1 m^3	10 m^3	100 m^3	Scaled to X_0
BGO	22.3×22.3×280 mm	$8/cc	$7/cc	$6/cc	1.23
BaF_2:Y	31.0×31.0×507.5 cm	$12/cc	$11/cc	$10/cc	2.28
LYSO:Ce	20.7x20.7x285 mm	$36/cc	$34/cc	$32/cc	1.28
PWO	20x20x223 mm	$9/cc	$8/cc	$7.5/cc	1.00
BSO	22x22x274 mm	$8.5/cc	$7.5/cc	$7.0/cc	1.29
CsI	35.7x35.7x465 mm	$4.6/cc	$4.3/cc	$4.0/cc	2.09

BaF2 Neutron Irradiation

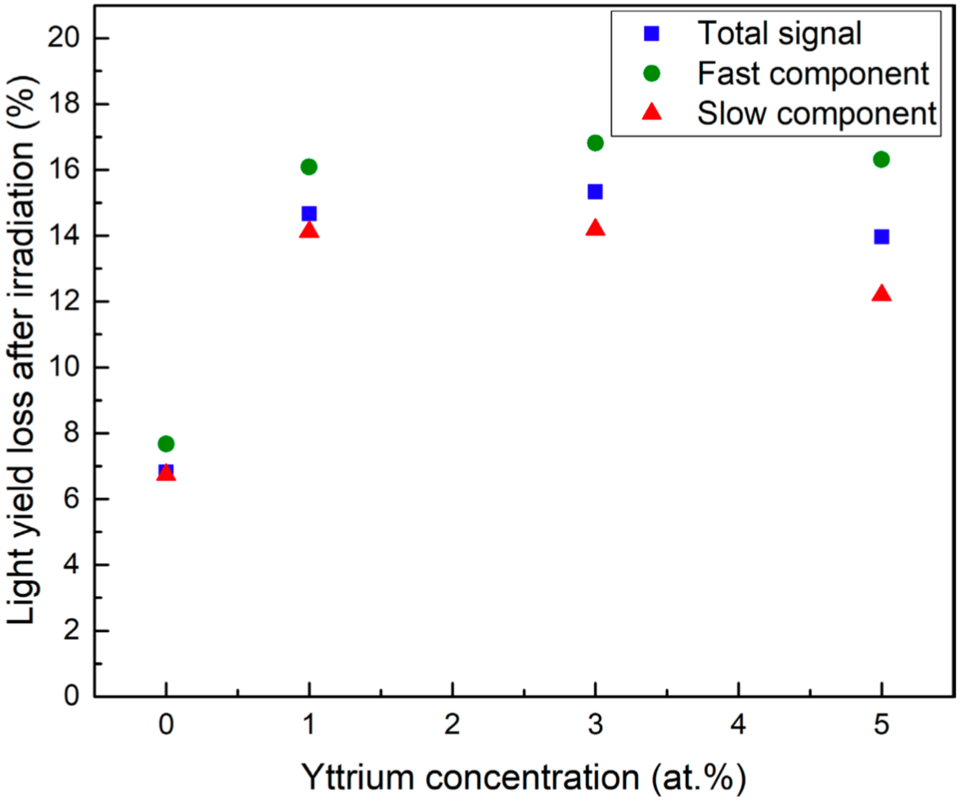
Yuri's talk

For the first session of neutron irradiation, only four samples (1x1x1 cm^3) produced by SICCAS were selected: one pure BaF_2 crystal and three samples doped with yttrium in the proportion of 1 at.%Y, 3at.%Y and 5at.%Y

- All four samples were placed together about 5 m from the water moderator
- During the 14-day reactor cycle about 2.3×10^{14} n/cm^2 (E>1MeV) passed through the samples
    - All samples were measured before and after irradiation
    - Light outputs were measured using ^{22}Na source
    - Signals were digitized by CAEN NDT5751
    - The total signal from the BaF_2 samples was measured for 2 µs, the fast component during the first 20 ns, and the slow component after 20 ns

Light yield loss after irradiation

Yuri's talk



V. Baranov, Yu.I. Davydov, I.I. Vasilyev 2022 *JINST* **17** P01036

- The light output loss of the pure BaF_2 crystal is about 7%.
- The light output loss of the yttrium doped samples is approximately two times higher than that of the pure BaF_2 sample.
- In all yttrium doped samples the light output loss of the fast emission component is 2-3% higher than that of the slow emission

Plan to irradiate samples in an electron beam at the Linac-200 accelerator at JINR in a few months

Photo-detectors

David's talk

- A **large area SiPM**, with **delta-doping** (a super-lattice) for improved speed and QE, and an integrated ALD-applied **interference filter**

  → Caltech and JPL are working with FBK to incorporate a 220nm filter on a large area SiPM and to also incorporate a superlattice.

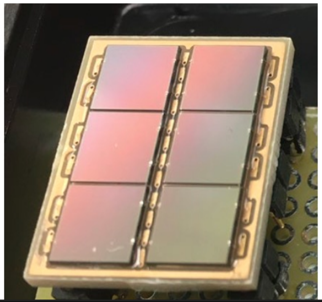
DONE
1. Build a three-layer ALD filter on a 6x6 mm NUV SiPM structure, exploring different SiNx passivation layers, guard ring structures, …
2. Fabricate 2x3 arrays of the 6x6 mm chips, biased in series parallel configuration à la MEG and Mu2e to read out larger crystals

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

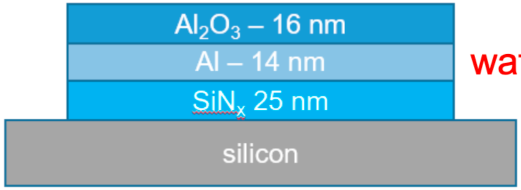
Not funded
- Fabricate back-illuminated SiPMs with a five-layer filter and delta-doping

Configuration is identical to that for Mu2e:



FBK SiPM with three-layer filter

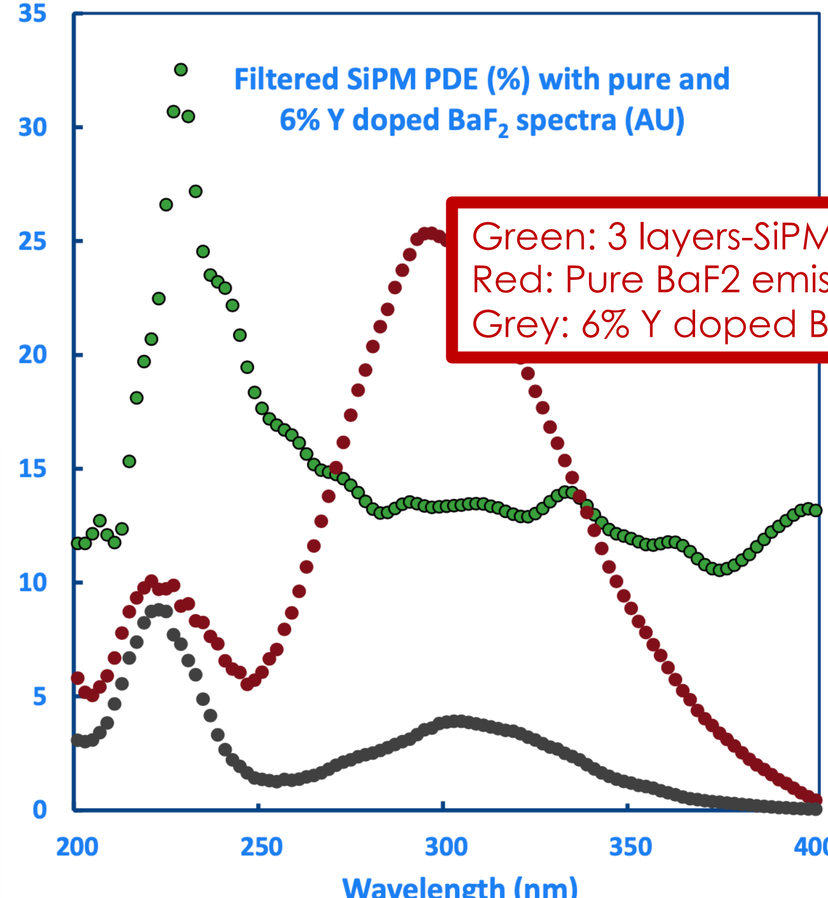
David's talk

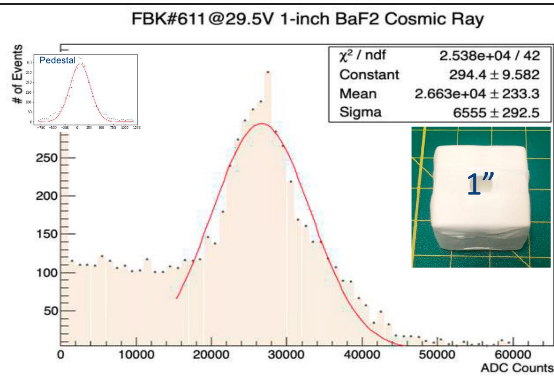


wafer 11

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

measurement



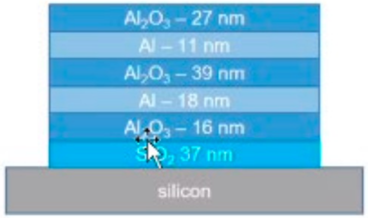


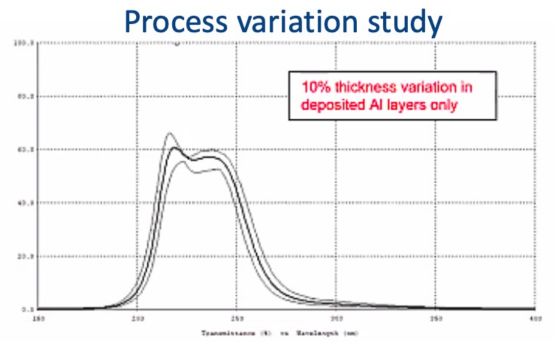
- FBK SiPM #611, dimension 6x6 mm, operated at 29.5V
- BaF_2 dimension 1” x 1” x 1”, wrapped with teflon with an opening of 6x6 (mm)
- Cosmic ray deposits 6.374 MeV/cm * 2.54 cm = 16.2 MeV
- (26631 - 68) adc / 148 pe/adc = 180 pe
- 180 pe / 16.2 MeV = 11 pe/MeV   With 2x3 array, expect 60-70 pe/MeV

Next steps in the program

David's talk

1) Optimization of the MBE superlattice layer parameters
2) More complex filters will be incorporated (5 layers filter)





3) Backside illuminated SiPM with optimized superlattice

Awaits funding ~ 400k$

SiPMs radiation hardness

My talk

15 μm

Temperature [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	75.29 ± 0.01	12.56 ± 0.01	30.45 ± 0.01	46.76 ± 0.01
-5 ± 1	75.81 ± 0.01	14.89 ± 0.01	32.12 ± 0.01	46.77 ± 0.01
0 ± 1	76.27 ± 0.01	17.38 ± 0.01	33.93 ± 0.01	47.47 ± 0.01

10 μm

Temperature [°C]	V_{br} [V]	$I(V_{br}+4V)$ [mA]	$I(V_{br}+6V)$ [mA]	$I(V_{br}+8V)$ [mA]
-10 ± 1	76.76 ± 0.01	1.84 ± 0.01	6.82 ± 0.01	29.91 ± 0.01
-5 ± 1	77.23 ± 0.01	2.53 ± 0.01	9.66 ± 0.01	37.51 ± 0.01
0 ± 1	77.49 ± 0.01	2.99 ± 0.01	11.59 ± 0.01	38.48 ± 0.01

Neutrons irradiation: 14 MeV neutrons with a total fluence of 10^{14} n/cm^2 for 80 hours on a series of two SiPMs (10 and 15 μm)

At 10^{13} n_{1MeV}/cm^2:

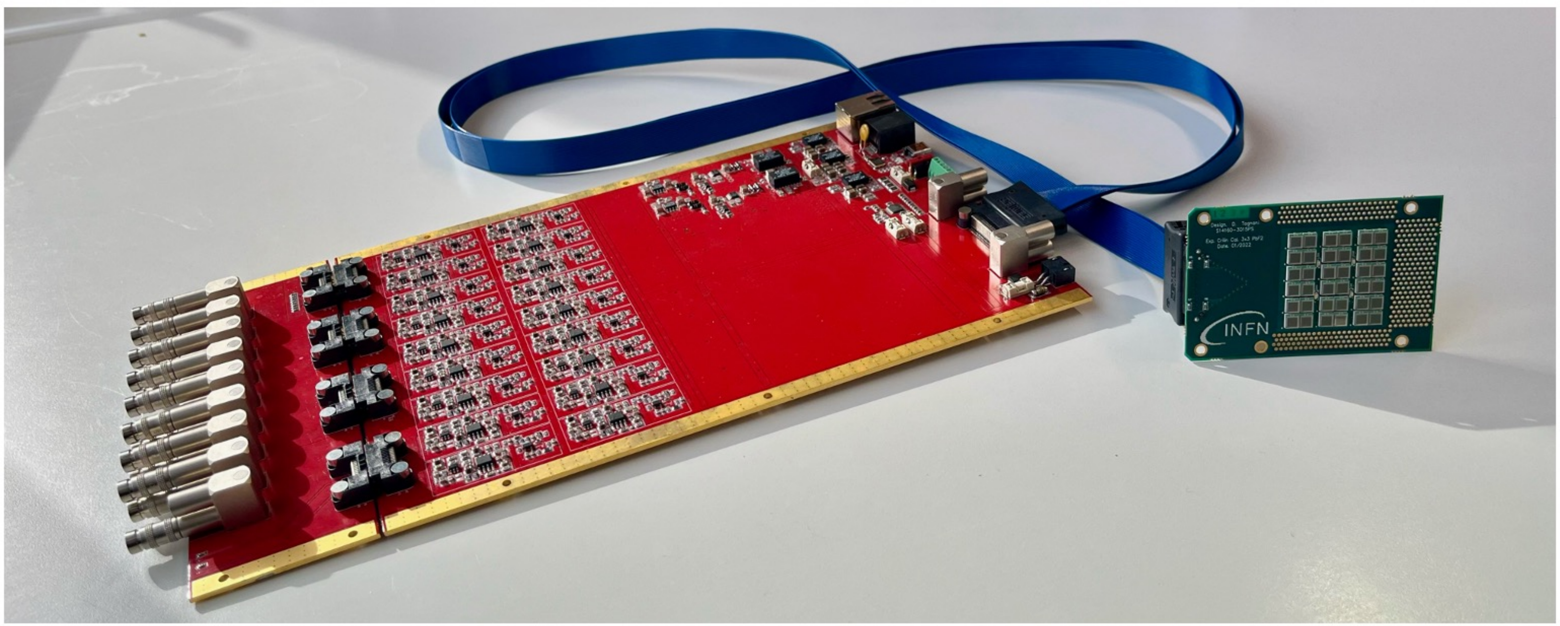
- 10 μm pixel size OK, with Mu2e calorimeter cooling system
- 15 μm pixel size OK, probably with the Mu2e calorimeter cooling system → specific tests should be done

Electronics

My talk

- SiPMs are connected via 50-ohm micro-coaxial transmission lines to a microprocessor-controlled Mezzanine Board which provides signal amplification and shaping, along with all slow control

  1 ch → 2 micro-coax cables



Short LYso crystal calorimetER - SLYER -

My talk

ADVANTAGES

- **8 cm length LYSO** are enough to achieved O(5%) energy resolution
- Not problem of ENE and good LRU
- Great timing resolution still after 10^{13} neutrons/cm^2
- SiPMs already exist **NOT R&D needed**
- High LY → SiPM @ low over voltage → enhanced resistance → lower power dissipation
- Not Front-End Amplifier is needed → not problems with irradiation level

DISADVANTAGES

- LYSO ~30$/cc vs ~10$/cc BaF2
  (17$/cc vs **10$/cc for equal X0)**

IS the pile-up rate acceptable with LYSO?
We need simulation

SLYER proposal:
Total cost of the LYSO crystals for the 2 disks = 3.8M$
(Mu2e: 20 cm CsI + FEE = 1.7M$ + 0.2M$)
(14 cm BaF2 + FEE = 2.2M$ + 0.2M$)

- *Emission time of 40 ns of LYSO vs <1 ns of BaF2*

Summary

Even if the requirement about the energy [**σ_E/E of O(10 %)**] and time [**$\sigma(t) < 500$ ps**] resolution remain the same, a big part of the detector and all the electronics **can't survive** to the new radiation environment

- ❑ To run Mu2e-II a new technological solution (crystal + photosensor) for the calorimeter is needed
  - - TID of about 600 krad and 1-MeV-eq n fluence of 5x10^12
  - - Signals with a maximum length of 75 ns, less is SM/ubunch will increase

Solar Blind SIPMs R&D should be concluded and tested the performances
- After neutron irradiation
- with BaF2:Y in dedicated test beam

LYSO + 10 um pixels SiPMs is a possibility → but dedicated simulations are needed