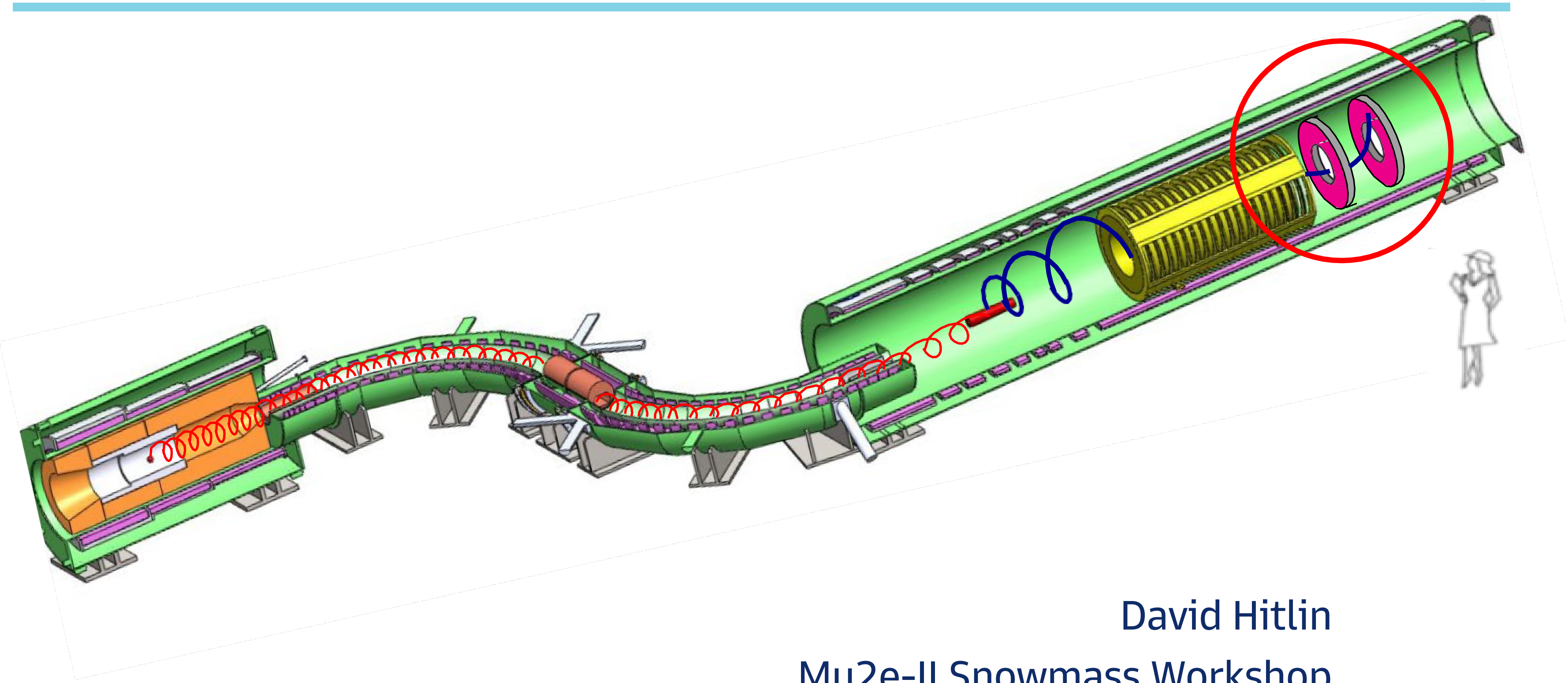
Status Report
Mu2e-II Snowmass21 Calorimeter Group



David Hitlin

Mu2e-II Snowmass Workshop

September 15, 2021

Frank's original charge

- "Our main item of discussion will be on issues related to whether we can handle increased beam over what has been the nominal plan. To be more explicit, I suggest:

- 1) That we take the 1.7 microsecond spill rate assumed for an aluminum stopping target
- 2) That we consider the possibility of a factor of four increase in protons in a spill, one factor of two from taking bunches at 162.5 MHz, and another factor of two from increasing the spill duration to 200 ns."

Mu2e-II Snowmass Calorimeter Group

- Convenors
  - David Hitlin,, Caltech
  - Luca Morescalchi, Convenor, INFN Pisa
  - Ivano Sarra, Convenor, LNF

- Léo Borrell, Bertrand Echenard, Dexu Lin, Sophie Middleton, James Oyang, Frank Porter, Liyuan Zhang, Renyuan Zhu - Caltech
- Eleonora Diociaiuti, Raffaella Donghia, Simona Giovannella, Fabio Happacher, Stefano Miscetti - LNF
- Stefano Di Falco, Simone Donati, Antonio Gioiosa, Elena Pedreschi, Franco Spinella - INFN Pisa

- There has been a limited amount of activity

The nominal situation

Mu2e Calorimeter Requirements

- Mu2e-II will endeavor to maintain the performance of the Mu2e calorimeter, in a somewhat more challenging environment, re-using as much of the existing system as possible

• Energy resolution	σ < 5% (FWHM/2.36) @ 100 MeV
• Time resolution	σ < 500 ps
• Position resolution	σ < 10 mm
• Radiation hardness • Crystals • Photosensors	 1 kGy/yr and a total of 10^{12} n_1 MeV equivalent/cm^2 total 3 x 10^{11} n_1 MeV equivalent/cm^2 total
• Provide an independent standalone trigger • Provide track seeding • e/μ particle identification (reject cosmic muons by > 200) with 90% efficiency for conversion electrons • Work in a 10^{-4} Torr vacuum:	

The Mu2e-II radiation environment

- **Frank's challenge corresponds to**

- ionizing radiation (40 kGy/yr or 4 Mrad/yr)
  - Total worst case dose ~10 Mrad
- neutron levels (4 x 10^{13} n_1 MeV equivalent/cm^2 total),
-

PIP-II/Mu2e-II:

- higher rates (**~x3**) and duty factor
- correspondingly higher ionizing radiation (**10 kGy/yr**)
- neutron levels **(10^{13} $n_{-1\ \mathrm{MeV\ equiv}}$/cm^2 total)**,

The worst case is at the inner radius of Disk 1, but radial falloff is not extreme.

Disk 2 dose is substantially lower

Nominal Mu2e-II Calorimeter Requirements

There will be 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

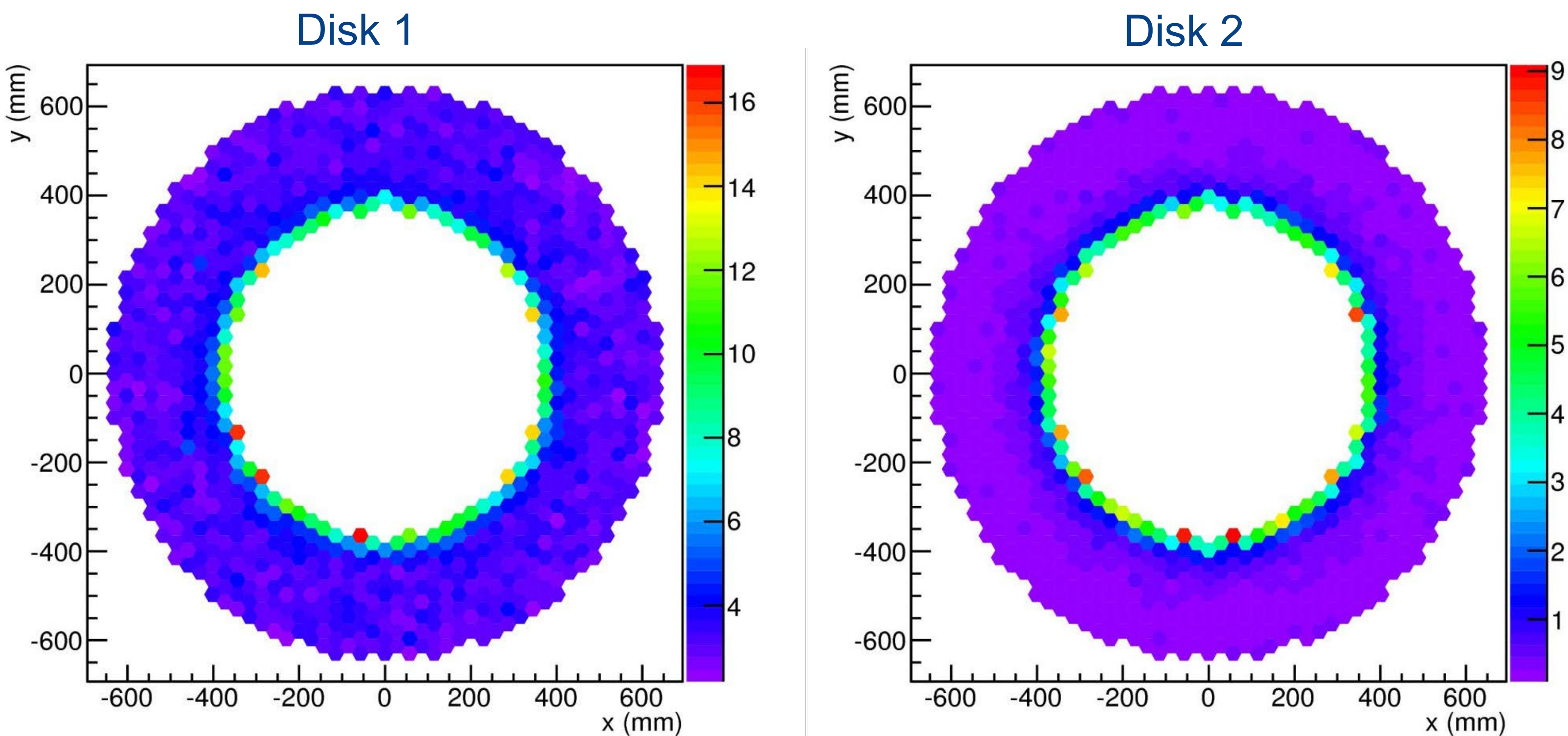
Disk 1 = 10 x 6 x 10^{10} x 5 x 3 = 9 x 10^{12}

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

Conclusion: We need, at least in 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 an R&D program aimed at finding viable solutions

Dose per crystal in kRad/year (Mu2e)



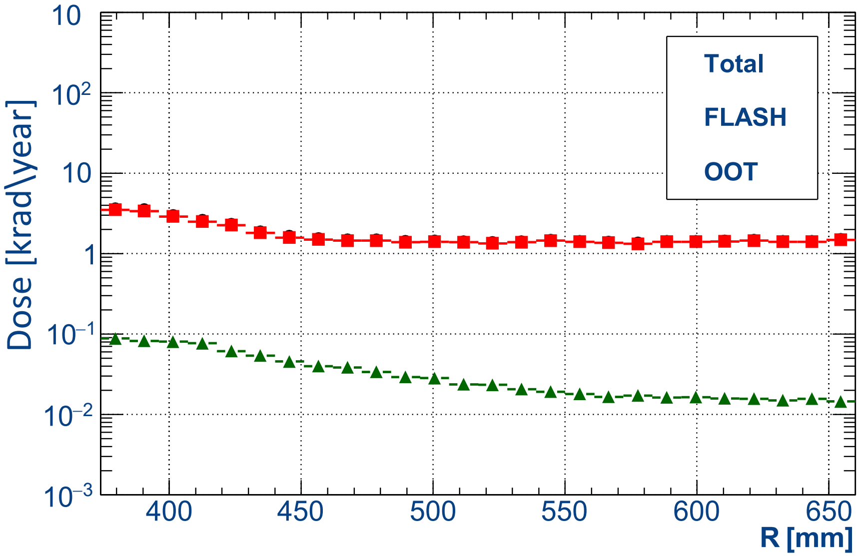
The average dose is around 3 (0.5) kRad / year for the front (back) disk, up to 16 (9) kRad / year for the innermost crystals in the front (back) disks

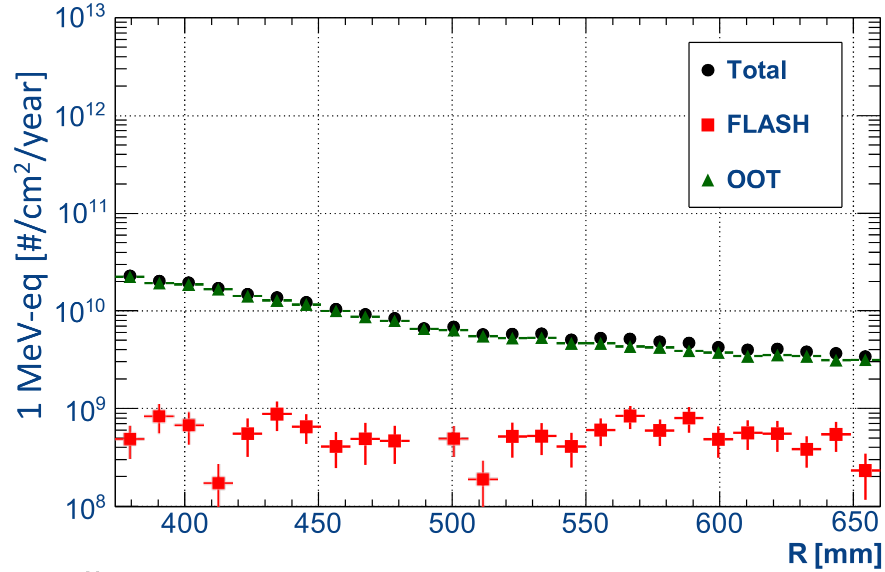
Echenard

γ Dose crystals — Neutron flux SiPMs

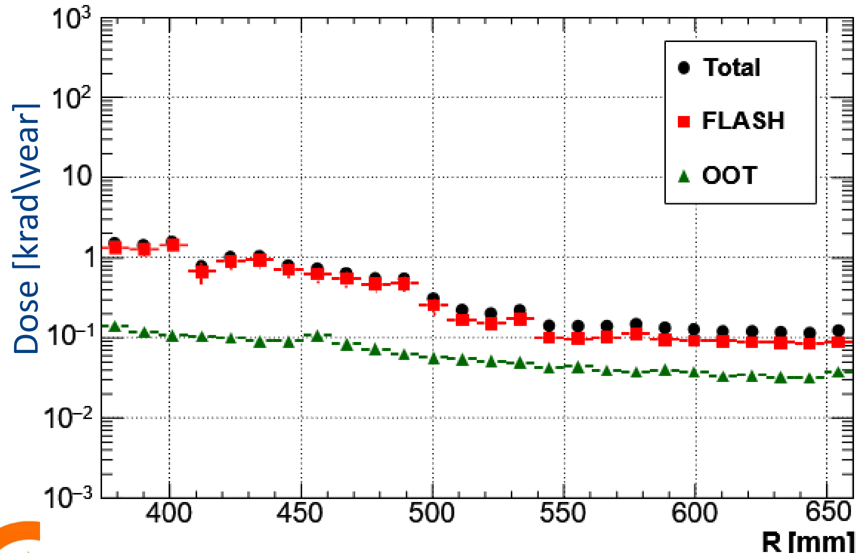
Mu2e

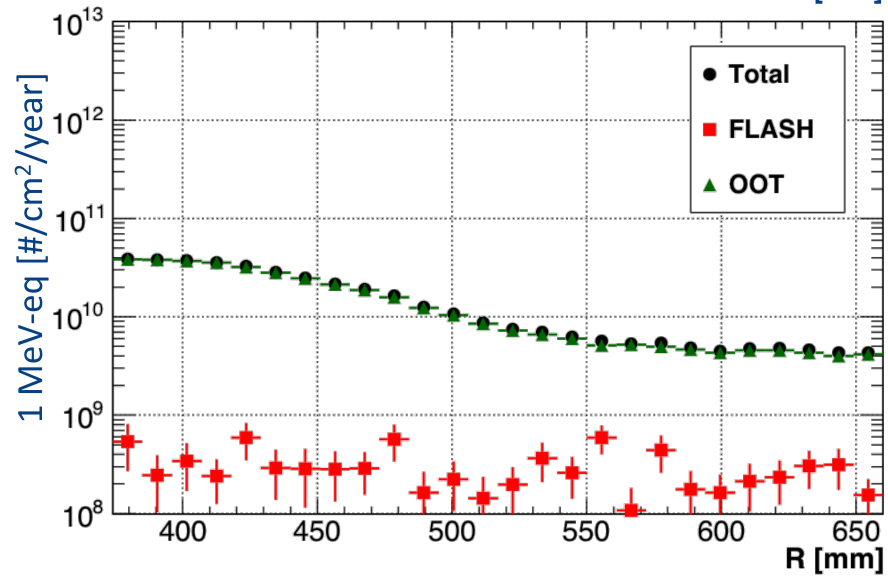
Disk 1





Disk 2



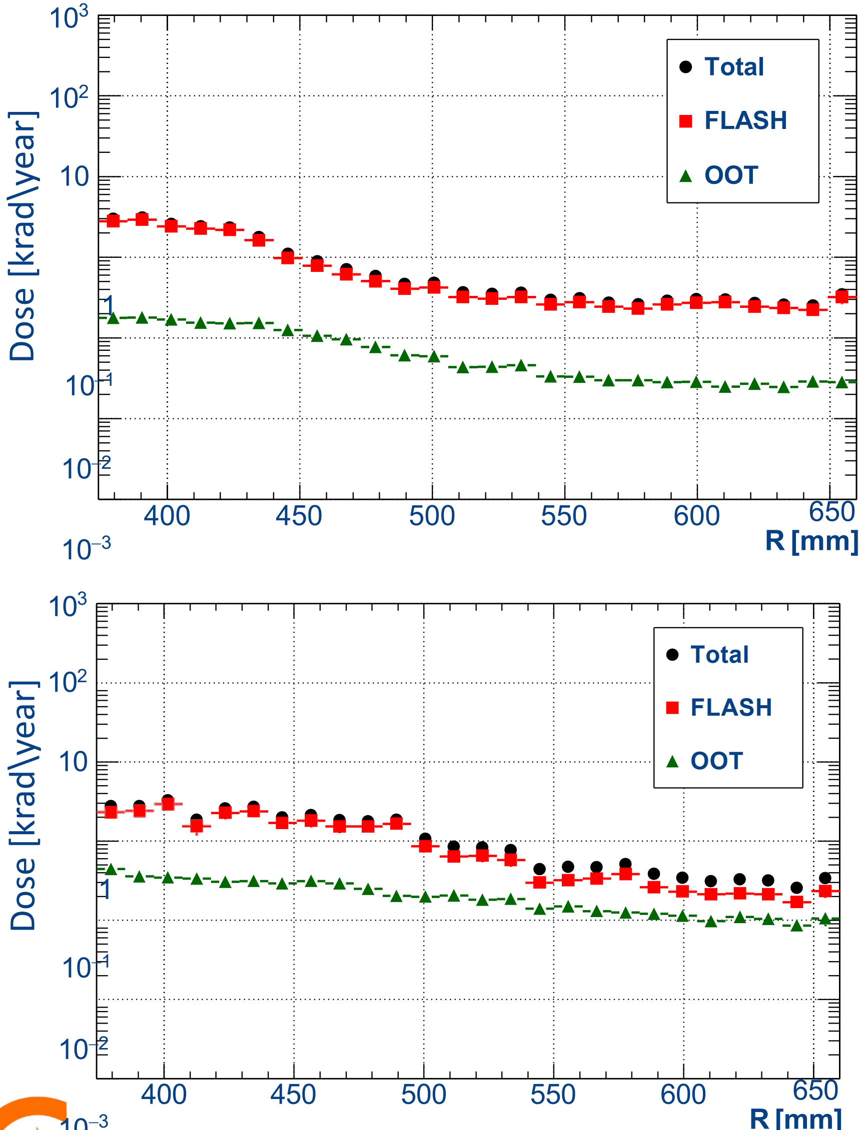


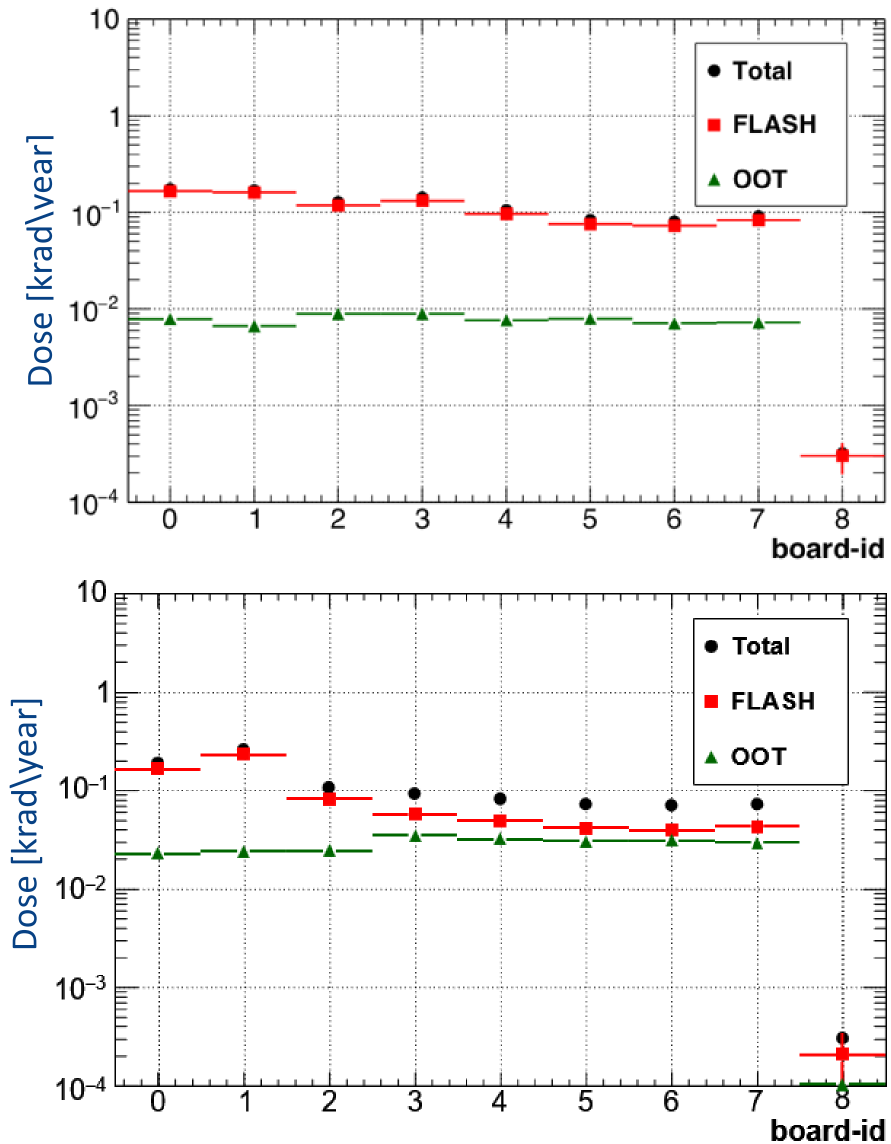
Mu2e

γ Dose – FEE   γ Dose – Dirac

Disk 1

Disk 2





Paper Status

- A Calorimeter Workshop was held on Sept 22, 2020

Agenda

Introduction and overview	Sarra	20
Doping of barium fluoride	Zhu	20
Measurements of doped BaF_2 crystals	Davydov	10
SiPM for the fast component of BaF_2	Hitlin	20
Sensors with nanoparticle filters	Magill	20
Solar blind MCP	Atanov	20
Next generation calorimeter DAQ	Spinella	20
Discussion		20

- There hasn't been sufficient response to subsequent queries to warrant another workshop
  - Reports have been mainly on the Caltech BaF_2 crystal/photosensor effort

- The paper will attempt to capture whatever R&D has been going on

Paper outline

1. Introduction
   - Mu2e requirements
   - Design to meet requirements
   - Mu2e-II requirements
2. Choice of crystal
   - Radiation hardness
   - Decay time
   - Development efforts
3. Choice of photosensor
   - Options
   - Development efforts
4. Data acquisition options
5. R&D program going forward

We will be seeking people to contribute sections.

Fast Inorganic Scintillators

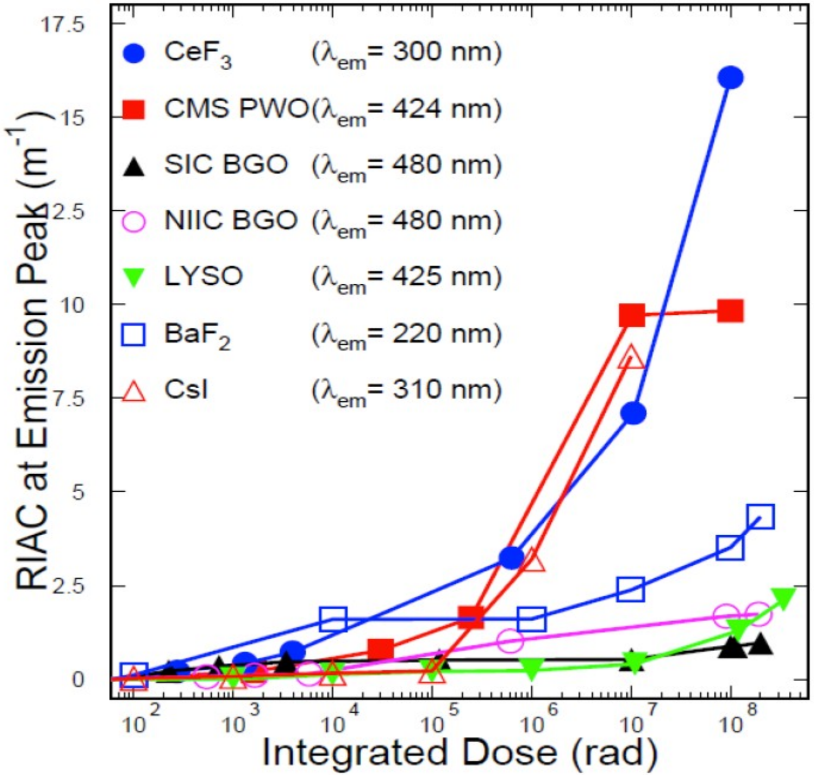
	GSO	YSO	LSO/ LYSO	CsI	BaF_2	CeF_3	$CeBr_3$	$LaCl_3$	$LaBr_3$
Density (g/cm^3)	6.71	4.44	7.4	4.51	4.89	6.16	5.23	3.86	5.29
Melting point (℃)	1950	1980	2050	621	1280	1460	722	858	783
Radiation Length (cm)	1.38	3.11	1.14	1.86	2.03	1.7	1.96	2.81	1.88
Molière Radius (cm)	2.23	2.93	2.07	3.57	3.1	2.41	2.97	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

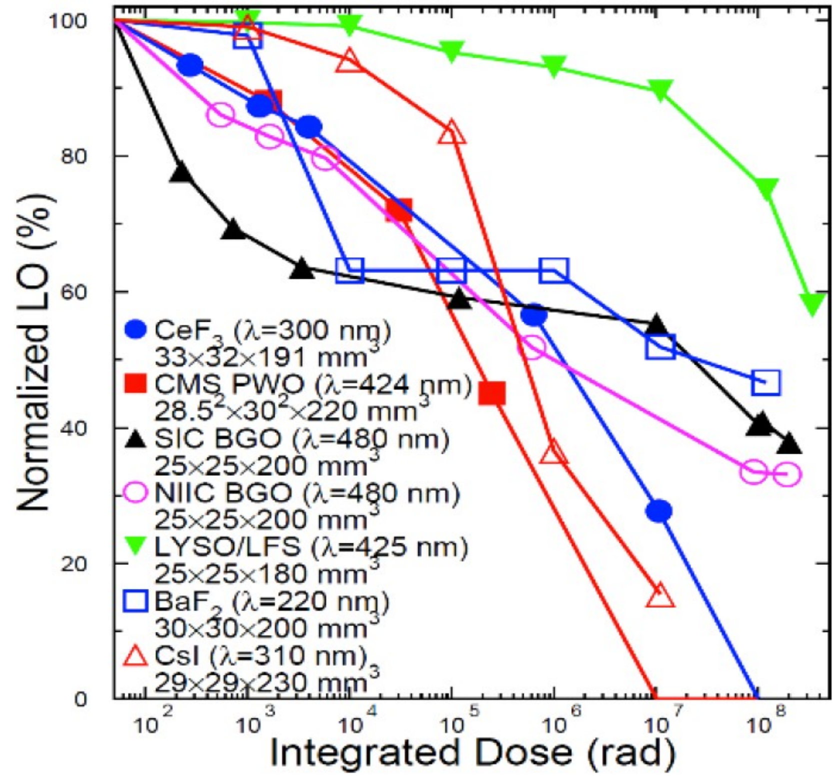
a. Top line: slow component, bottom line: fast component.
b. At the wavelength of the emission maximum.
c. Relative light yield normalized to the light yield of LSO
d. At room temperature (20°C) #. Softening point

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

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

Radiation hardness comparison





R.Y. Zhu

RIAC: radiation induced absorption coefficient

For radiation hardness, the leading candidates are BaF_2 and LYSO

Radiation hardness of Y-doped BaF_2

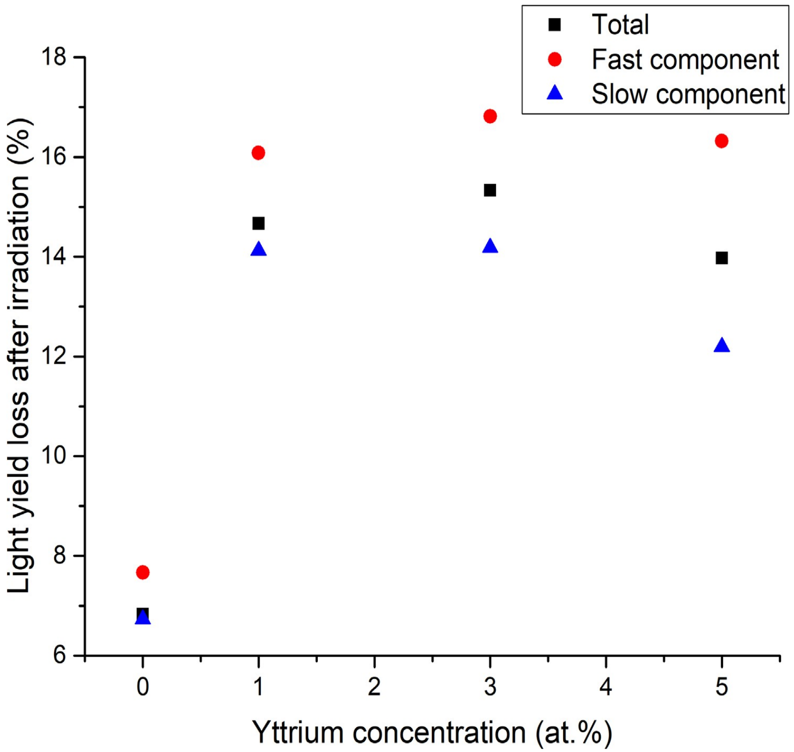
- Caltech plans to study the light output change of BaF_2(Y) under γ irradiation
  Dubna has done tests with reactor neutrons up to ~2.3×10^{14} n/cm^2 with BaF_2(Y) samples from SICCAS and BGRI
- In unirradiated samples, the slow signal is suppressed 3.6 times in the 1at.% doped sample, 7.2 times in the 3at.% doped sample and ~7.5 times in the 5at.% doped sample compared to the slow component of a pure BaF_2 sample

Fast emission LO, ph.e.

Y doping	0%	1at.%	3at.%	5at.%
Unirradiated	**57.4**	57.2	55.9	52.7
Irradiated	53.0	48.0	46.5	44.1
LO_{Irr}/LO_{Unirr}	0.923	0.84	0.83	0.84

Slow emission LO, ph.e.

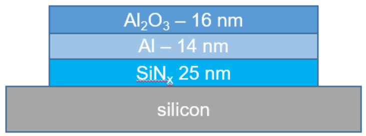
Y doping	0%	1at.%	3at.%	5at.%
Unirradiated	**526**	146	71	67
Irradiated	490	125	60	58
LO_{Irr}/LO_{Unirr}	0.93	0.856	0.845	0.866

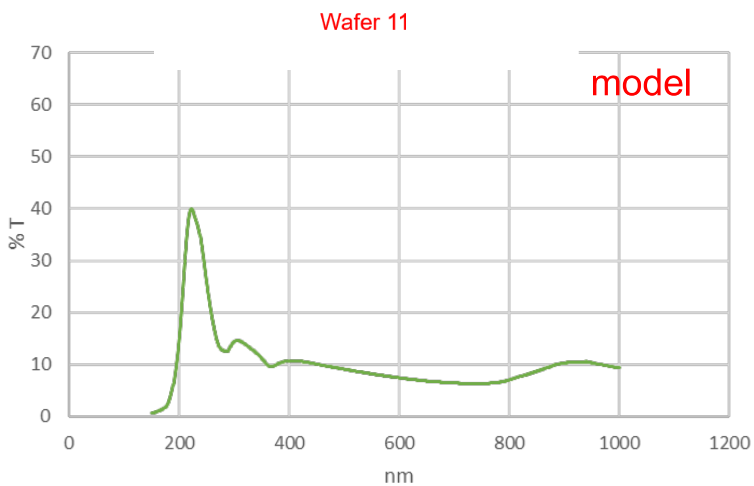


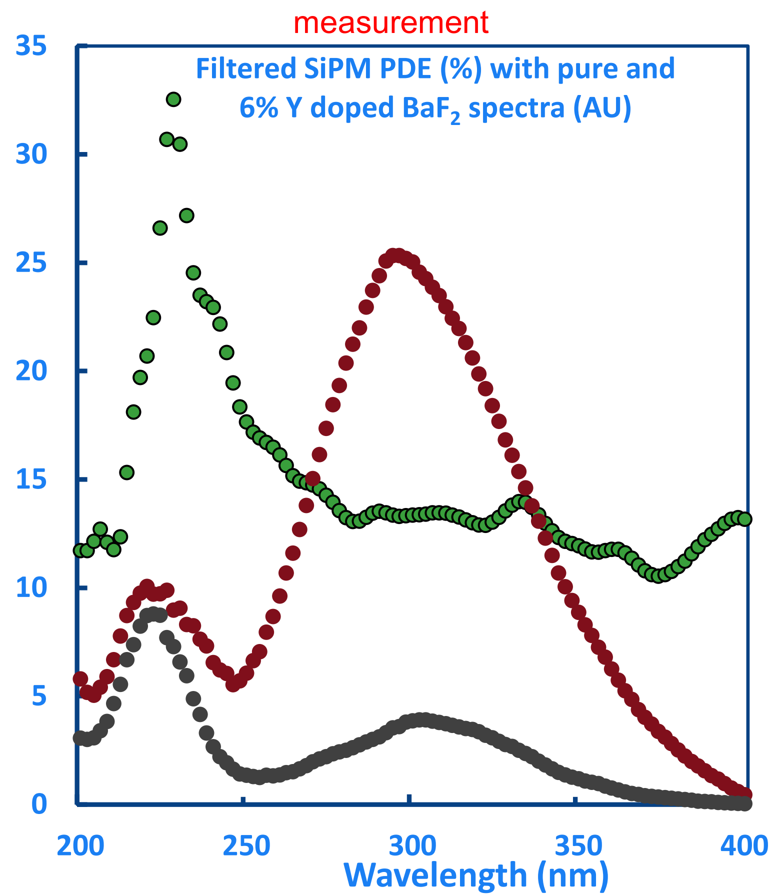
Y. Davydov

Photosensor

- The likely viable photosensor will be some type of SiPM
  - Conventional (UV-extended) SiPMs are compatible with LYSO and CsI
  - We have a first generation filtered UV-extended SiPM for BaF_2





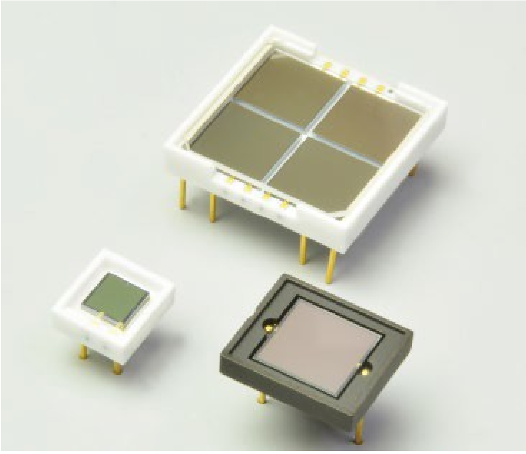


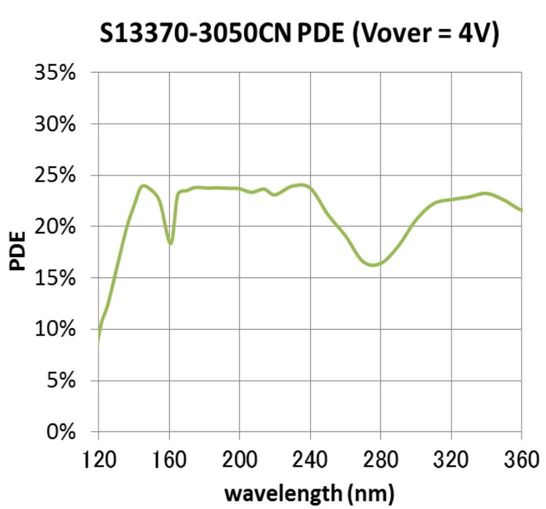
- Neutron dose is the largest concern
  - Reduced temperature operation is the response
- Pulse shaping will be required

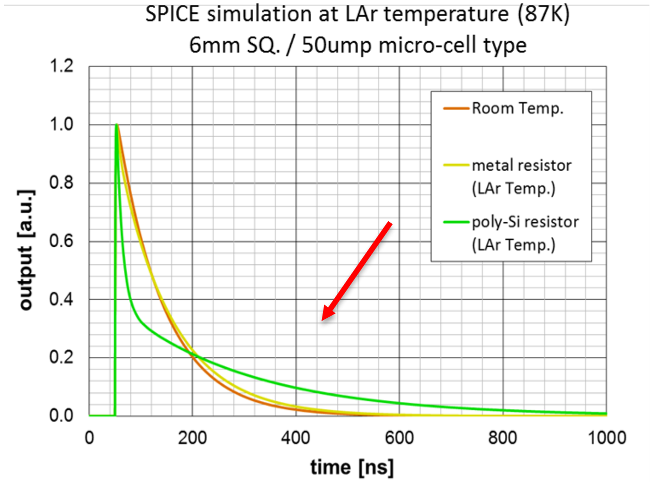
Hamamatsu VUV MPPC

S13370 series

- 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





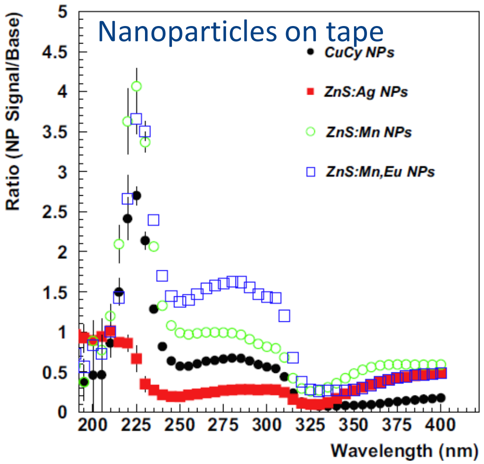


Series/parallel connection of 6x6 mm SiPMs, as in the current Mu2e calorimeter, improves decay time characteristics

- FBK also has excellent VUV SiPMs

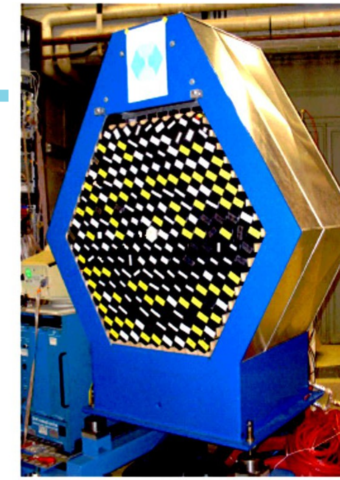
Photosensor options for Y-doped BaF_2

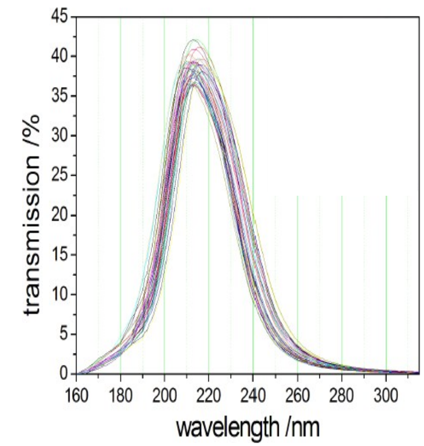
- We still lack an ideal photosensor for the rates of Mu2e-II
- What is required of an appropriate photosensor?
  - Spectral sensitivity in the 200 nm region for best energy and time resolution
  - Fast/slow component discrimination for high rate capability
  - Improved rise/fall time characteristics 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 50% 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)

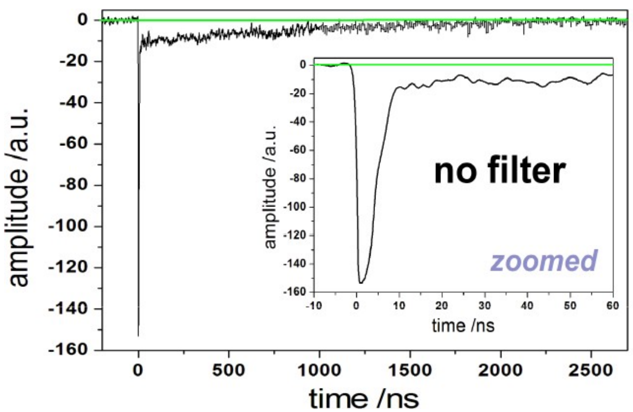


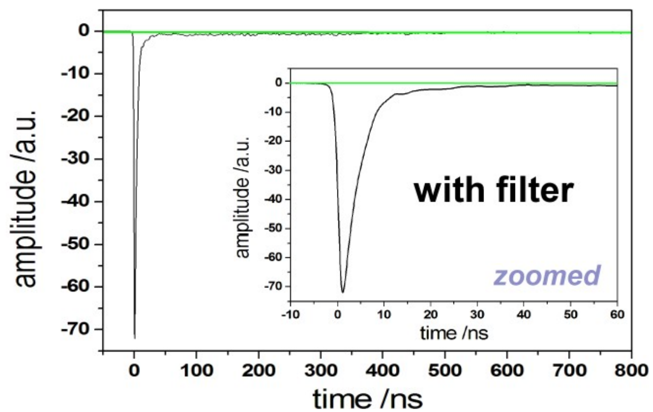
PMT + external filter

- 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 However, an filter integrated with the silicon sensor can achieve greater efficiency

Integrated approaches

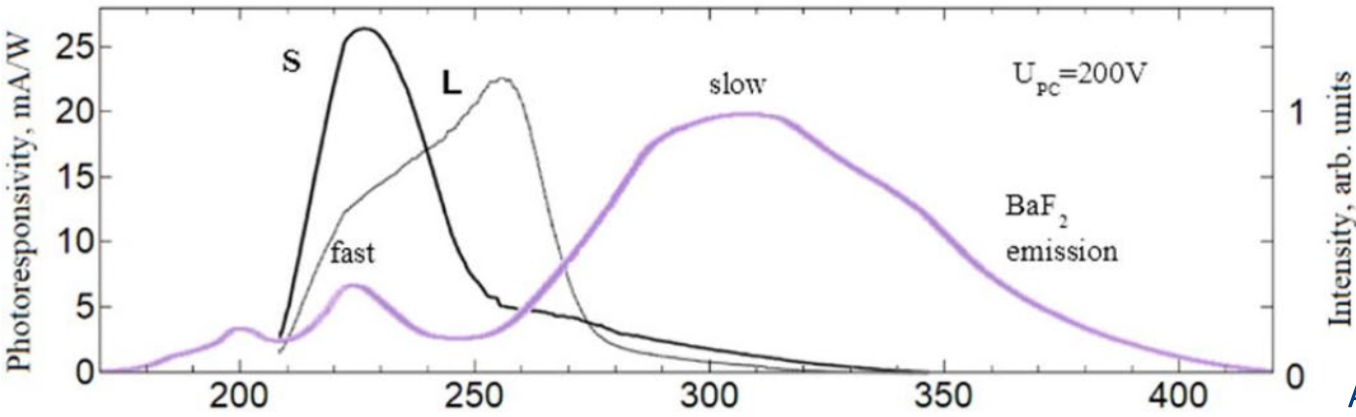
- The LAPPD, a channel plate PMT that works in a magnetic field, is very fast and potentially very attractive, but a great deal of R&D remains before we have practical device for use with BaF_2

    - Need either a photocathode with an extended UV response and a quartz entrance window (*i.e.*, no filter), or
    - An efficient filter and/or wavelength-shifting coating on the window
    - A size appropriate to the scintillating crystal Molière radius
    - An affordable price

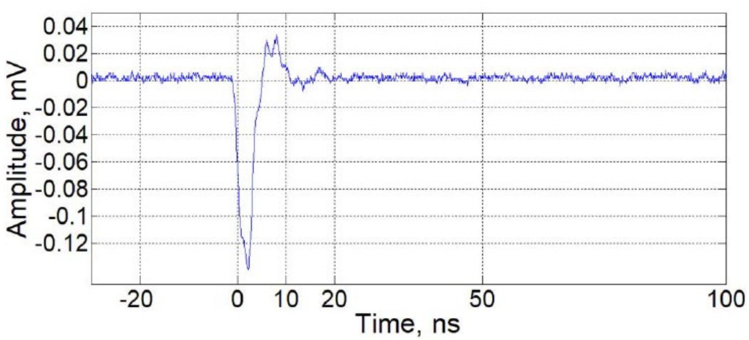
    - DH and RYZ had initiated an effort with ANL to develop an 8x8 cm LAAPD with a Cs_2Te UV-extended solar-blind photocathode
        - After preliminary discussions, this effort has been suspended

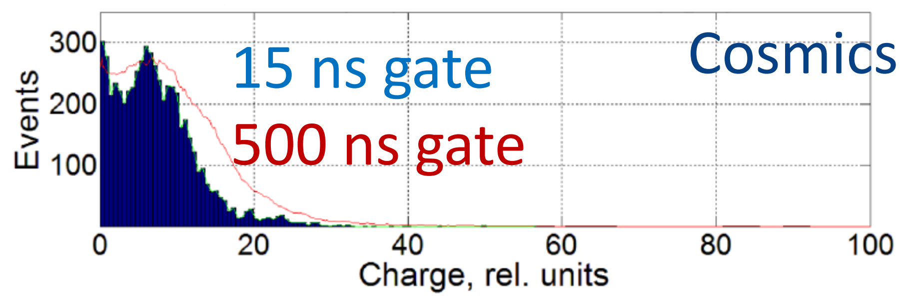
AlGaN photocathodes for an MCP

- 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



Atanov, et al.

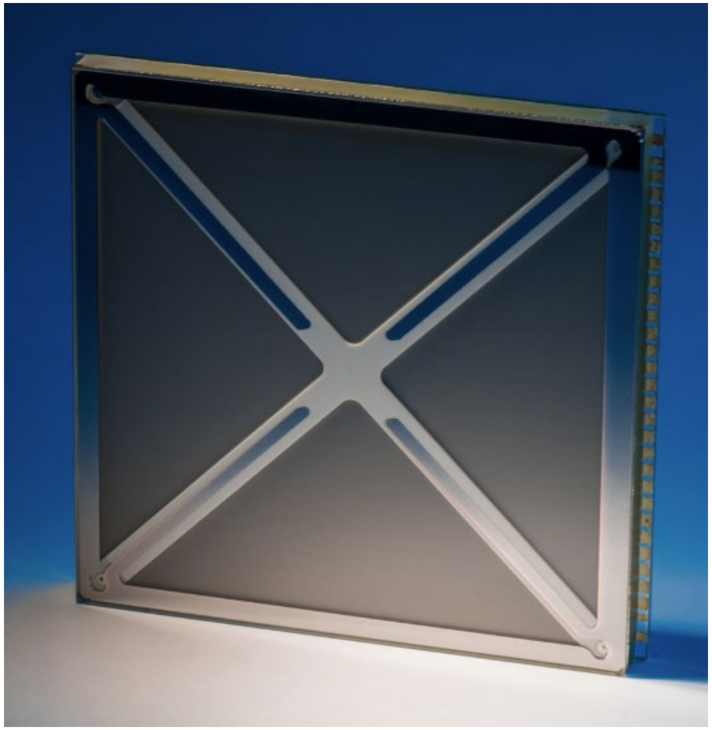




What is the lifetime in total charge at the anode of the MCP?

LAPPD with solar blind photocathode

- The LAPPD, a channel plate PMT now produced by Incom in 20x20cm size, is very fast and potentially very attractive, but much R&D remains before we have 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



An abortive attempt to develop such a device using existing equipment was launched by ANL/Caltech, but was killed when ANL HEP Division management changed

What is the lifetime in total charge at the anode of the MCP?

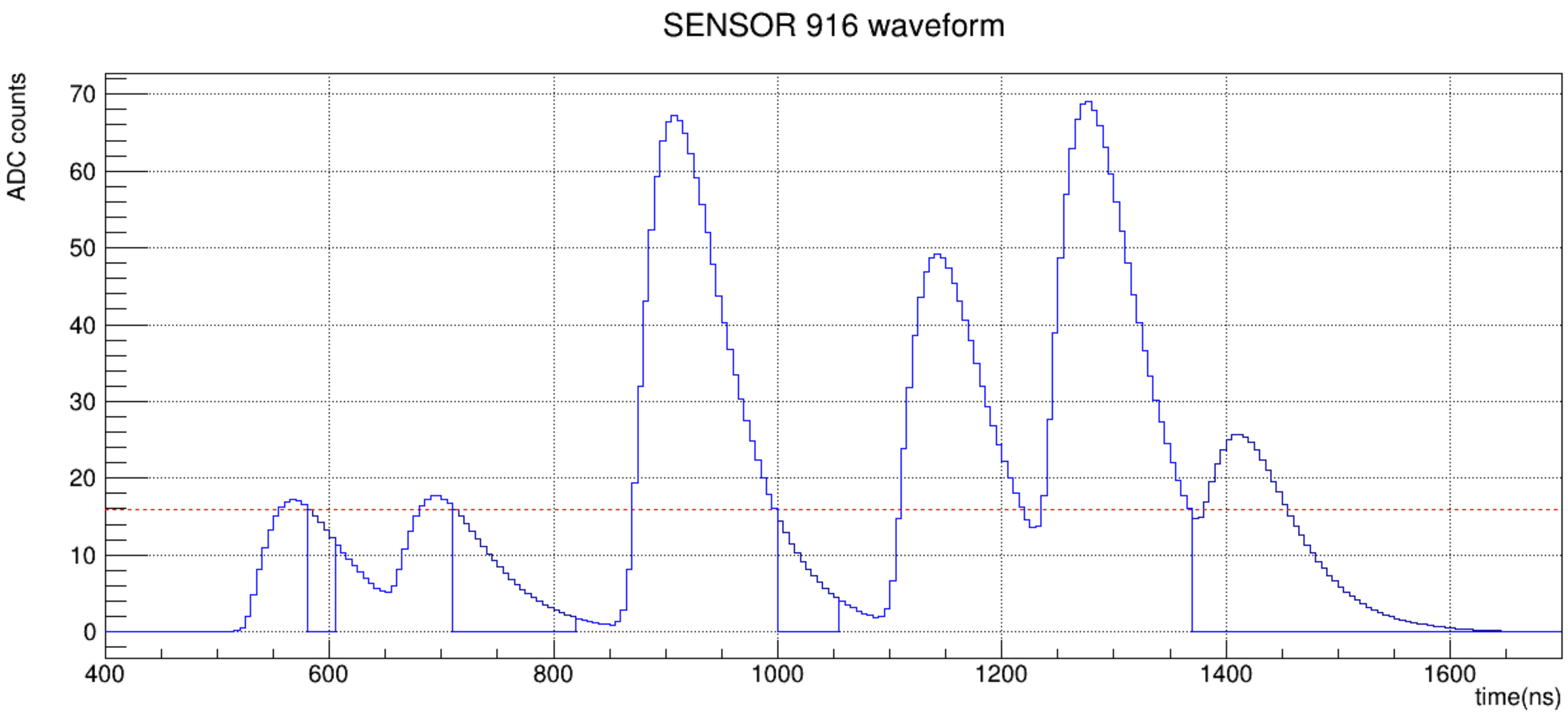
Mu2e

- Mu2e-II beam luminosity is 3x; we will have 3 times more hits …
  - We have to change detector strategy … (pile-up explosion …)
- Let’s assume the same architecture: crystal + photodetector, and almost the same specs: timing resolution $\mathcal{O}$ 200 ps, energy resolution $\mathcal{O}$ 10 %
  - We need faster crystal (BaF_2, …) and faster analog electronics (shaping amplifier)
- Assume shaped signal width $\mathcal{O}$ 30 ns with a rise time $\mathcal{O}$ 5 ns

- Mu2e readout is based on 200 MHz 12 bit ADCs, shaper is tuned for rise time $\mathcal{O}$ 25 – 30 ns so we can have 5-6 samples to calculate t_0.
- We need a different readout scheme to reach the same requested $\mathcal{O}$ 200 ps timing resolution

Mu2e event

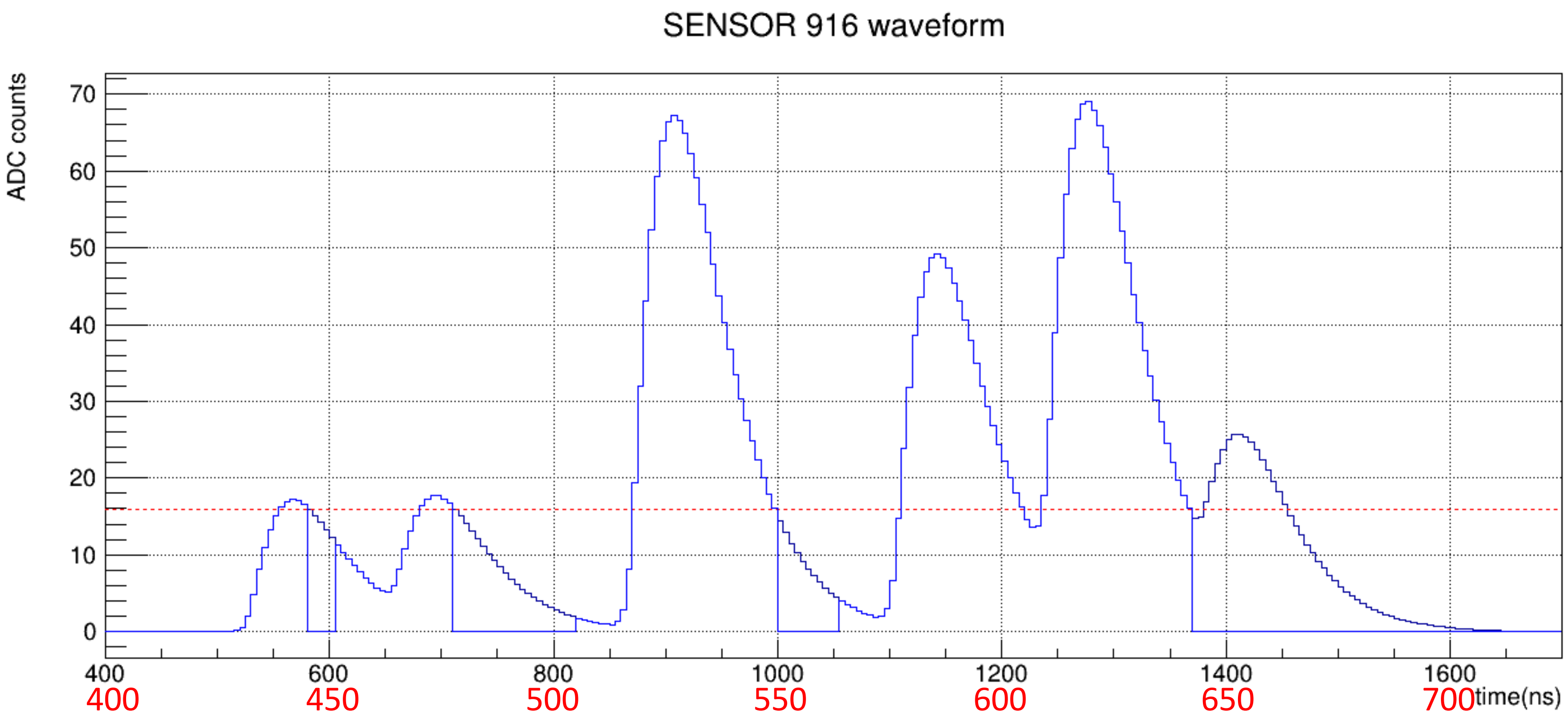
- ❑ Current Mu2e ecal event (simulation, 1 channel, inner ring, crowded ...)



- One hit 100-200 ns
-

Mu2e event ⇨ Mu2e-II event

❑ Current Mu2e ecal event (simulation, 1 channel, inner ring, crowded ...)



- One hit 100- 200 ns
- One hit 30- 50 ns

Luca's comments on DAQ

- At the moment it isn't possible to say what the maximum rate capability we will be able to sustain in Mu2e-II from the point of view of the electronics.
  - This will depend on the technology that will be available at the moment
  - the main concern, as Franco Spinella showed in his workshop talk, will be the **radiation hardness of available components**. In principle, many technical solutions are available at different price points.
  - Assuming BaF_2 as the crystal and a generic photosensor + an amplifier/shaper that produces a 30 ns signal, the only real physical limitation (meaning no engineering problem that cannot be solved with money or with future technology) is the pileup.
  - I have heard of a hypothetical factor of 100 increase in the intensity.
    - Assuming that it there is duty factor change x3, the instantaneous luminosity increases by a factor of 33.
    - Assuming a current mean occupancy for the inner ring channels, of 1, each channel would have 33 hits to extract following the muonic atom decay probability function; this would be quite difficult to resolve even with a very fast ADC. So the limitation is the number of 30 ns hits that we can resolve in a microbunch. If we want a stable system, we have to add a factor from 3 to 5 for beam intensity fluctuations.
    - Increasing the calorimeter inner radius can mitigate the problem by a small amount.

Readout techniques

- Ultra Fast ADC (>1 GHz …) – 5x sampling frequency
  - Solves pileup problem
  - High bandwidth, 10 gbit links
  - Expensive
  - High power
  - Needs expensive FPGA. Radiation hardness ?
- TDC
  - Good time resolution
  - PicoTDC under development at CERN
  - Does not necessarily solve pileup issue
- TDC + ADC
  - Can solve pileup problem

- Radiation hardness at a Megarad is challenging
  - PicoTDC ok …
  - FPGA ? Today (2020) only Xilinx Virtex5-QV space grade FPGA are qualified for dose 1 MRad(Si) but $$$$$$
  - ADC ? Need to be qualified …

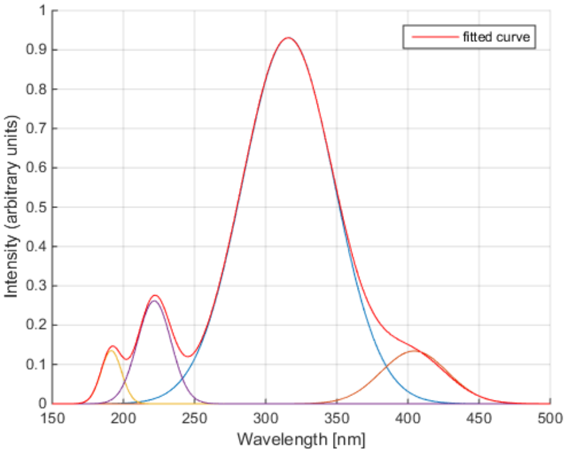
Spinella

Mu2e-II calorimeter subgroup

- The only R&D effort that has been communicated to our subgroup over the last year or so is the work at Caltech on doped barium fluoride and on a SiPM for BaF_2 readout
- Neither of these efforts is currently funded
  - COVID-19 restrictions have impacted the work, but there has been some progress
  - We have submitted three proposals seeking funding
    - Rothenberg Innovation Initiative (Caltech) – not funded
    - DOE Advanced Detector Research – excellent reviews, but not funded
    - Caltech/JPL President’s and Director's Research and Development Fund – not funded
- We want to organize another calorimeter workshop, but we haven’t detected sufficient activity to warrant one
  - Other potential avenues of inquiry include different crystals (*e.g.*, LYSO), nanoparticle wavelength shifters, microchannel PMTs, LAAPDs, …

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

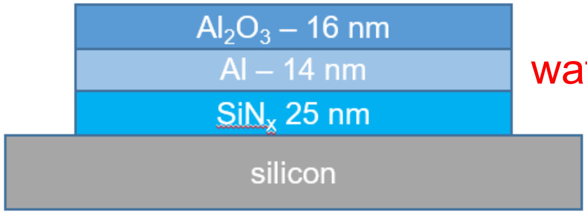
  Suppress the BaF_2 slow component by Y doping, as developed by Zhu *et al.*,: a major advance, although R&D remains to be done

  Develop a SiPM that is sensitive only to the fast component

  This is being done by a Caltech/JPL/FBK collaboration:

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

FBK SiPM with three-layer filter

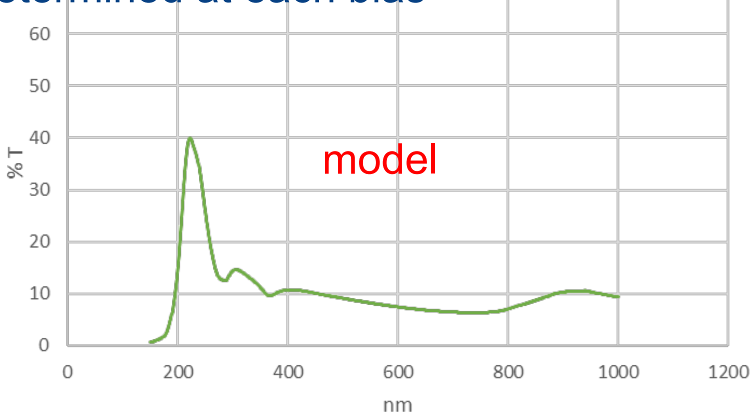


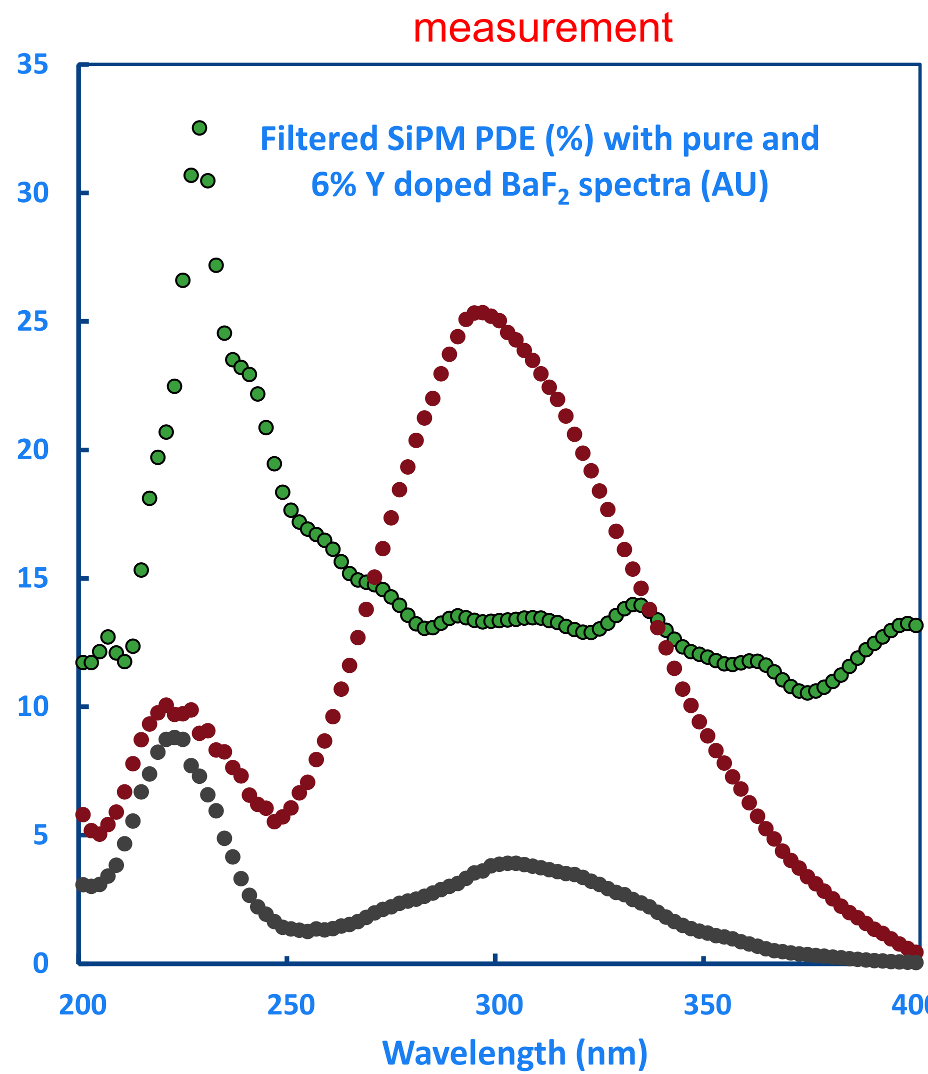
wafer 11

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

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

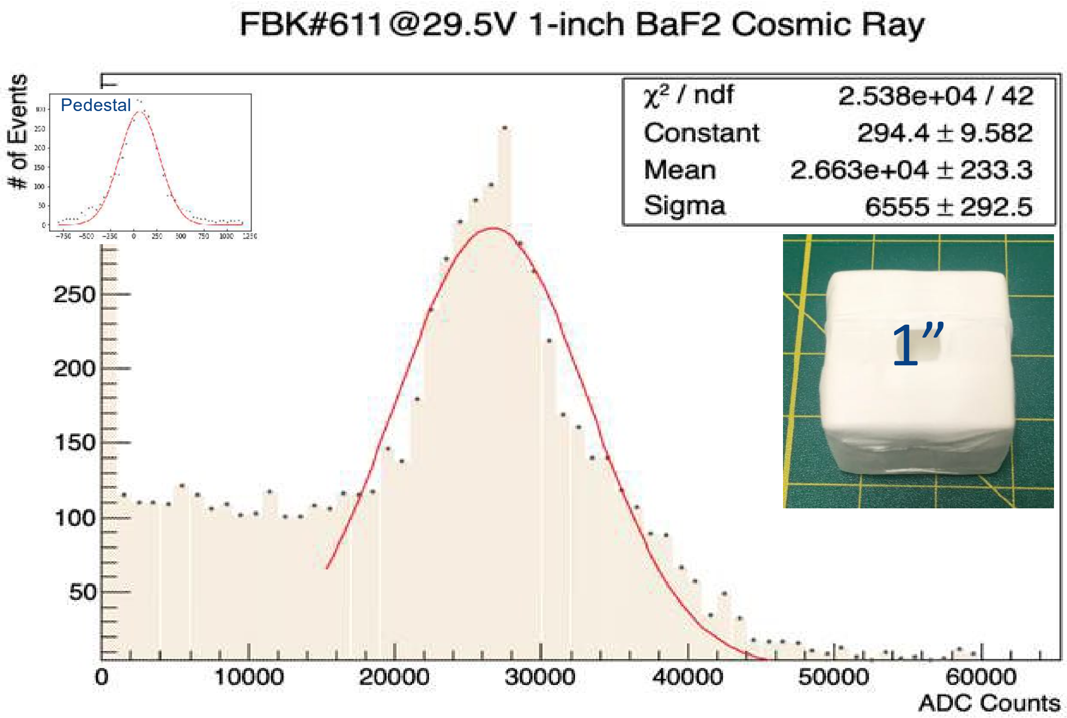
Excess noise factor determined at each bias





L. Zhang, J. Oyang

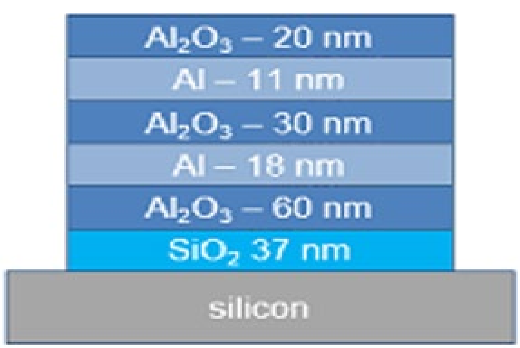
FBK #611 BaF_2 Cosmic Ray Spectrum

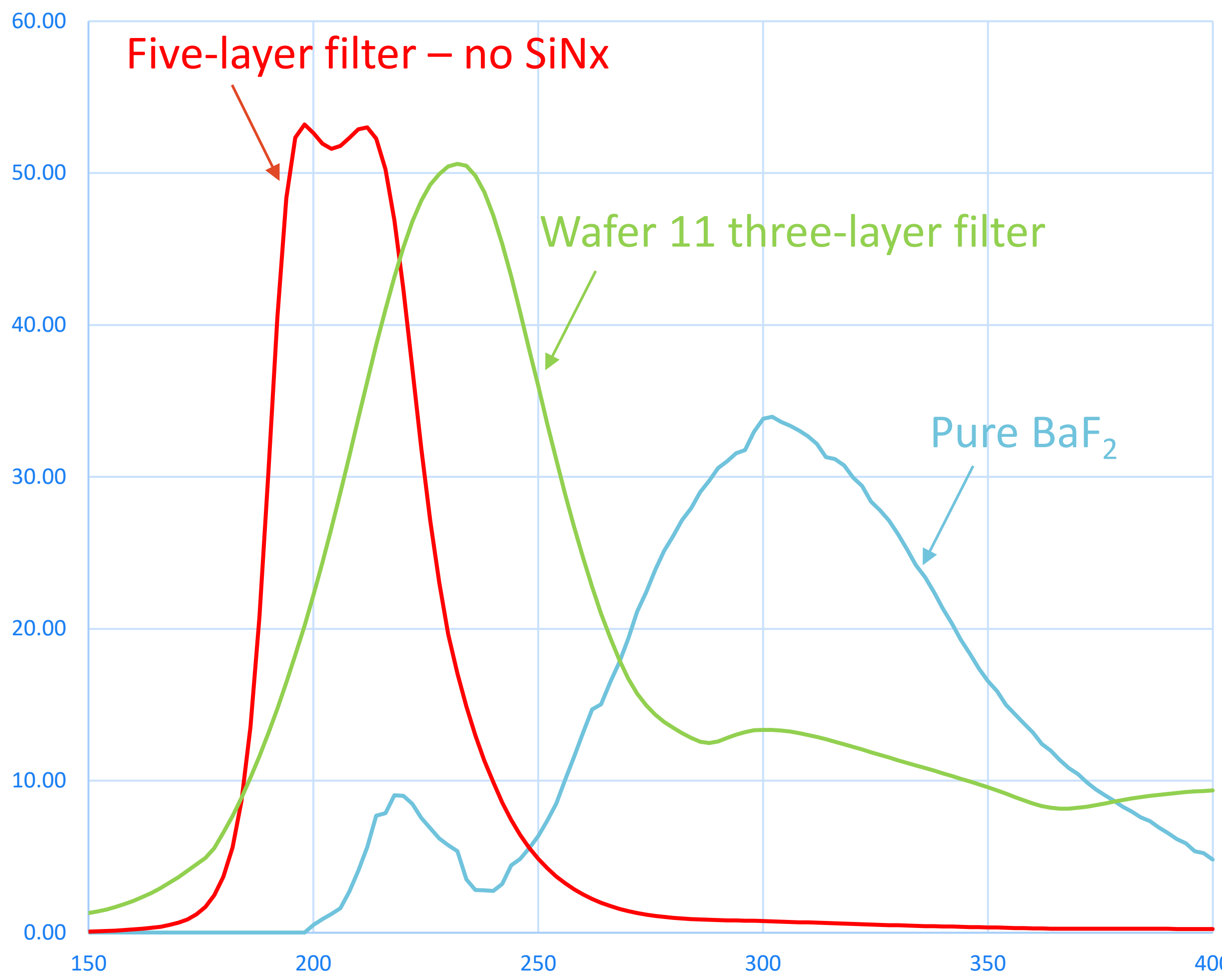


- FBK SiPM #611, dimension 6x6 mm, operated at 29.5V
- BaF_2 dimension 1” x 1” x 1”, wrapped with teflon with an opening of 6x6 (mm)
- Cosmic ray deposits 6.374 MeV/cm * 2.54 cm = 16.2 MeV
- (26631 - 68) adc / 148 pe/adc = 180 pe
- 180 pe / 16.2 MeV = 11 pe/MeV With 2x3 array, expect 60-70 pe/MeV

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

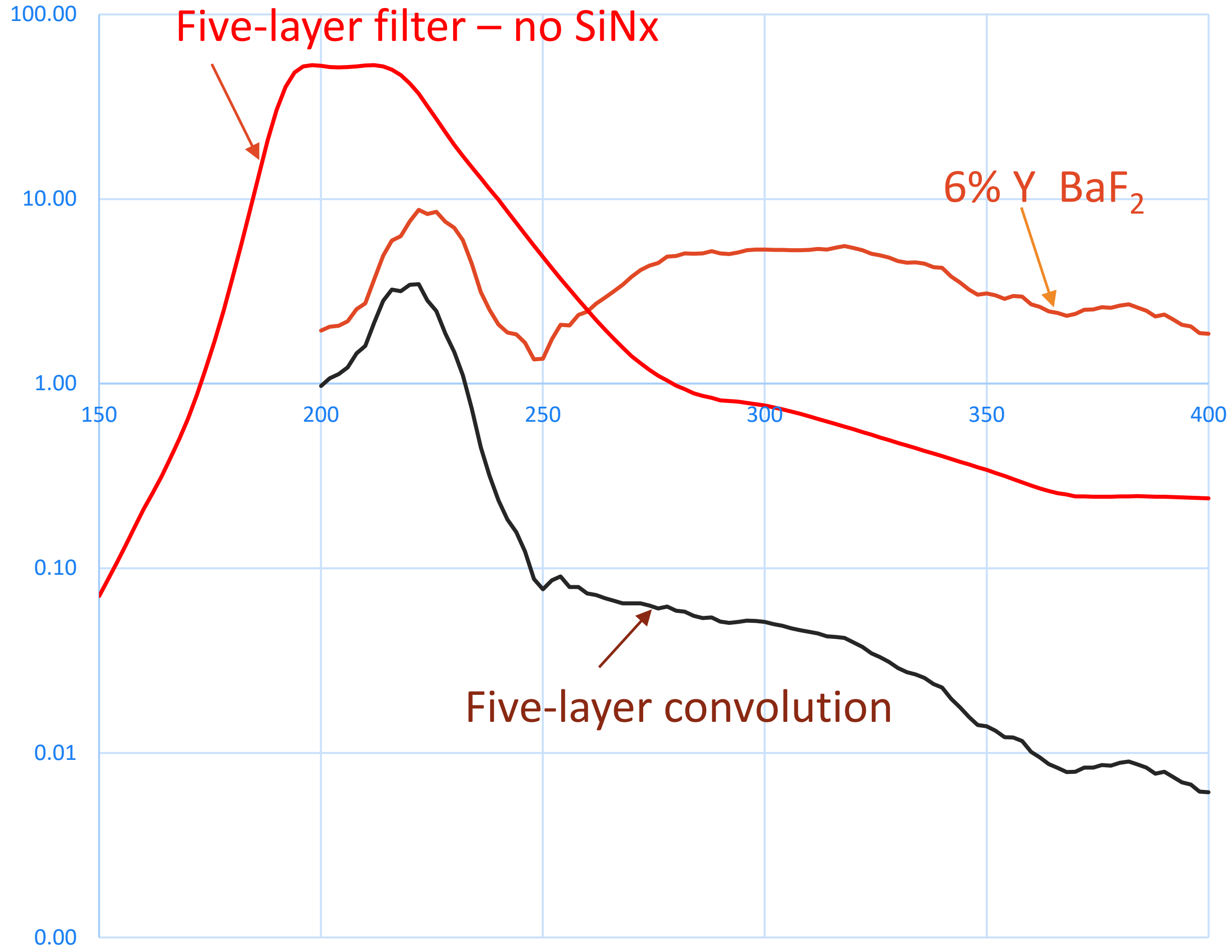




Further improvement of fast/slow performance

- 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 and other high-rate applications



CIT/JPL/FBK SiPM - a phased approach

- 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

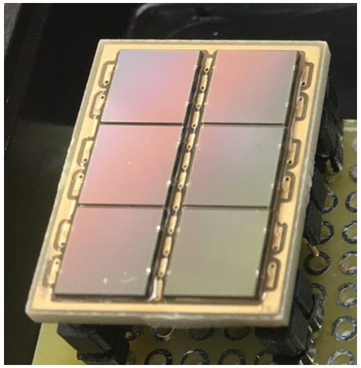
Unfunded

4. Use delta doping and backside illumination to improve PDE, the effectiveness of the filter and timing performance
   - First explore parameter space of MBE fab of delta-doping using diode structures of various sizes – reticles have been produced
   - Then fab back-illuminated SiPMs with five-layer filters and delta-doping

Estimated layer thicknesses April 2021

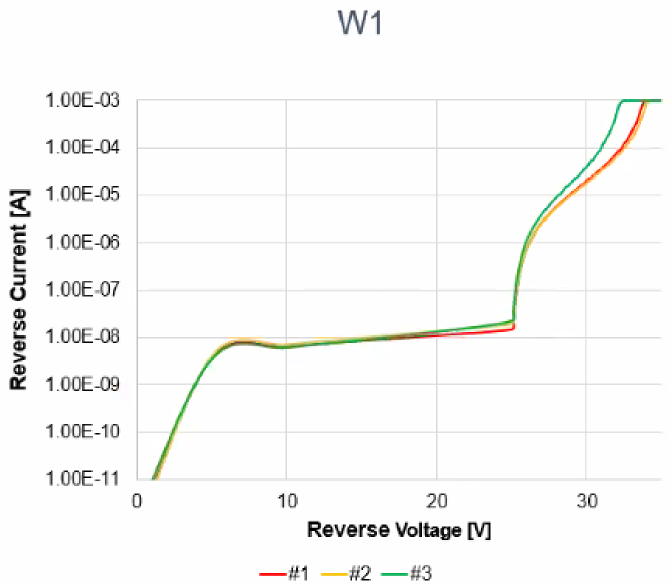
- JPL now has access to their ALD and MBE facilities
- We have now produced new five-layer filters on two existing wafers

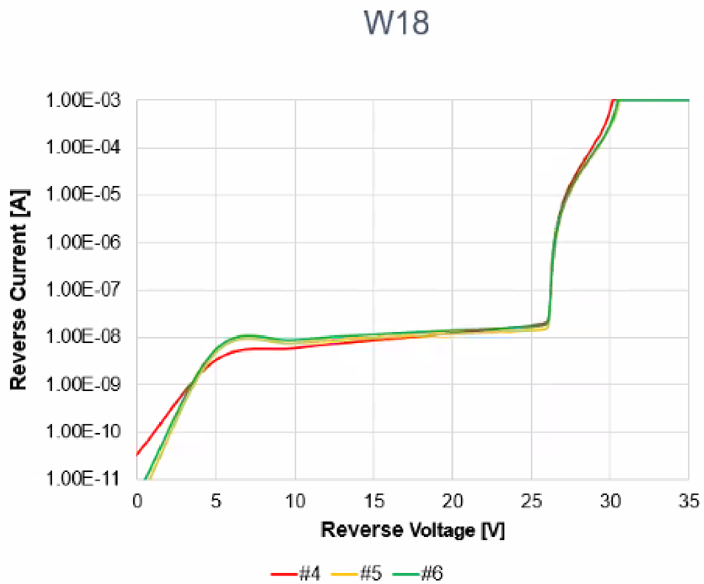
- FBK wafers 1 and 18 have pre-existing passivation layers of SiN and SiO_2 respectively
- Dummy wafers B0330 and B0401B were also produced for etch testing, starting with bare silicon only
- These wafers have been sent to FBK for electrical testing, dicing into 6x6 mm chips and production of 3x2 arrays of the 6x6 mm chips
- Devices for measurement of PDE (6x6 mm) were shipped to Caltech yesterday. (3x2 arrays) for readout of large BaF_2 crystals will be shipped in a few weeks



IV curves for new wafers

IV measurement





FBK IRIS INTEGRATED RADIATION AND IMAGE SENSORS

3

Next steps – not currently funded

- We succeeded, using an SBIR grant with RMD several years ago to produce large area back-illuminated APDs with filters for the BaF_2 fast component
- SiPM structures are much more complex
  - We have adopted a two-phase approach
    1. Fabricate diode structures of varying sizes in order to use measurements of leakage current with many area vs. perimeter ratios to understand the effect of
       - Different etching procedures on metallization and other surface structures
       - Different MBE formulations

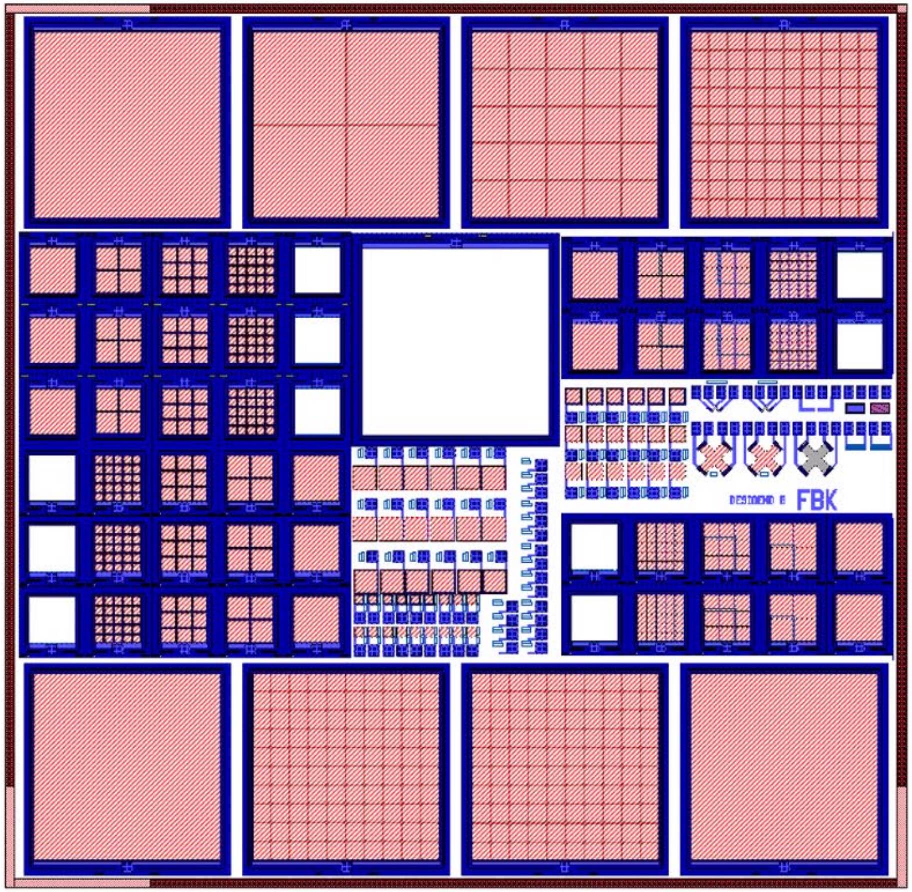
       on device electrical performance
    1. Use this information to optimize deep, delta-doped and filtered SiPM structures that can be back-illuminated

Photodiode wafers

FONDAZIONE BRUNO KESSLER

Shot composition

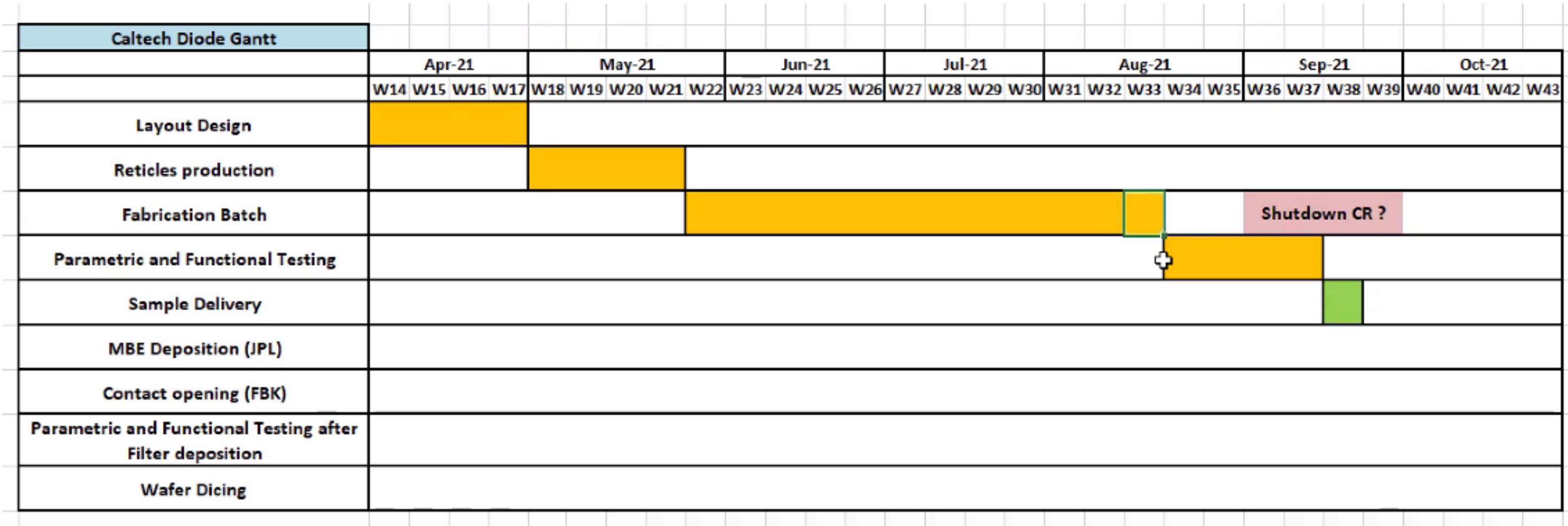
Splits	Layout	AA/SIR Overlap	Trench/ SIR
1	L1	Overlap1	no Dist
2	L1	Overlap2	no Dist
3	L1	Overlap1	Dist1
4	L1	Overlap2	Dist1
3	L1	Overlap1	Dist2
4	L1	Overlap2	Dist2
5	L2	Overlap1	no Dist
6	L2	Overlap2	no Dist
7	L2	Overlap1	Dist1
8	L2	Overlap2	Dist1
7	L2	Overlap1	Dist2
8	L2	Overlap2	Dist2
9	L3	Overlap1	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

Photodiode production schedule



Conclusions

- Further development of crystals (uniformity of Y doping in BaF_2), radiation hardness (ionizing and neutrons) is needed
- Further development of an appropriate photosensor is needed
  - Need neutron irradiation tests
  - Very low temperature performance should be verified
  - Other ramifications of low temperature, such as effect on tracker must be studied
- Partial solutions such as replacing portions of a disk may be viable
- The choice of crystal and photosensor for the Mu2e-II calorimeter will drive the design of the readout system
  - The DAQ system will be challenging
    - Several architectures needs to be carefully evaluated
- We will need both simulations and laboratory prototypes to choose the best solution in terms of performance (bandwidth and radiation hardness) and cost
- Work is ongoing in crystal, sensor and DAQ areas