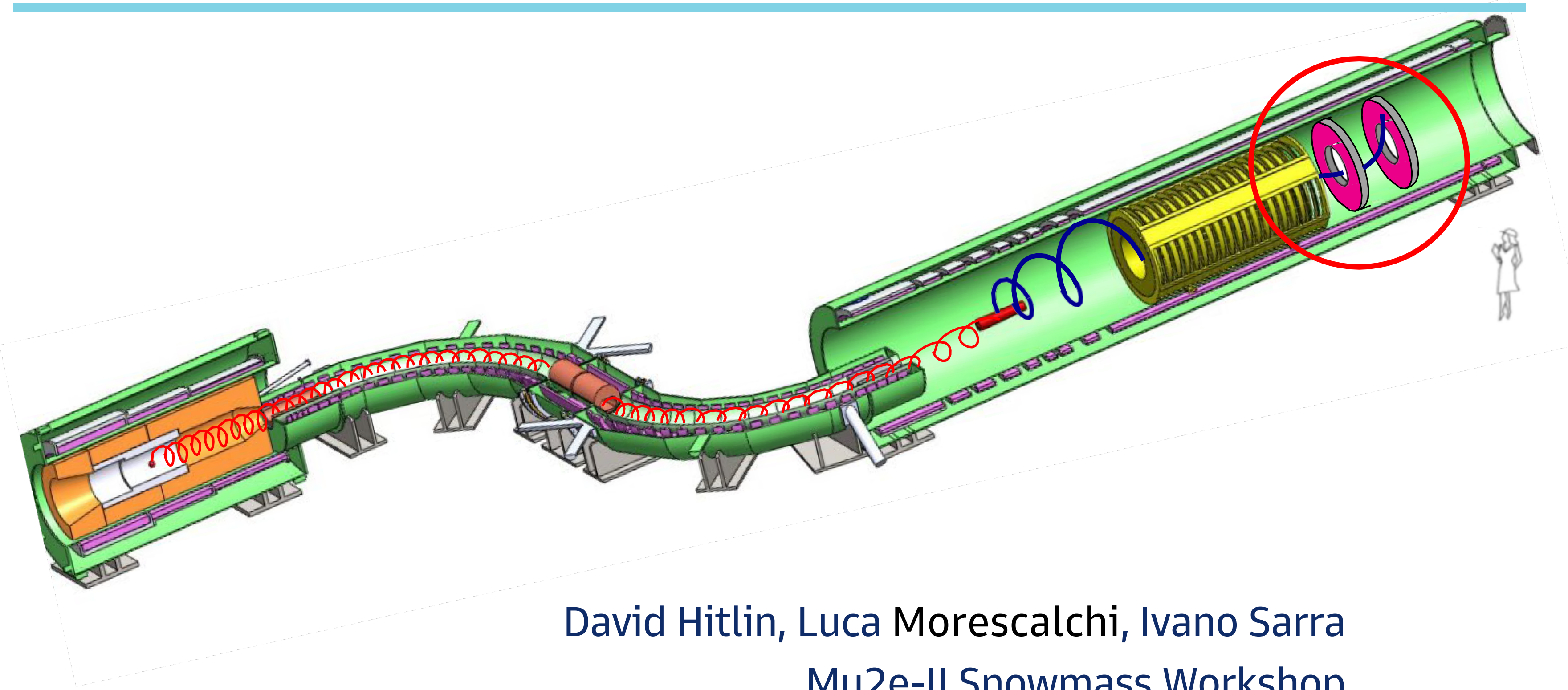
Status Report
Mu2e-II Snowmass21 Calorimeter Group



David Hitlin, Luca Morescalchi, Ivano Sarra

Mu2e-II Snowmass Workshop

August 26, 2020

Calorimeter Requirements

- Mu2e-II will endeavor to maintain the Mu2e calorimeter performance requirement in a 10^{-4} Torr vacuum:

• 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	

while facing **higher rates (~x3) from PIP-II** and correspondingly higher ionizing radiation (10 kGy/yr) and neutron levels (10^{13} n_1 MeV equivalent/cm^2 total), which are particularly important at the inner radius of disk 1

Calorimeter Requirements

There will be higher rates, neutron flux and ionizing dose 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 x 6 x 10^{10} x 5 x 3 = 900 x 10^{10} = 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 fast radiation hard scintillator, an appropriate photosensor, and a data acquisition system that can support the crystal/sensor performance

Simulation tools exist to explore the parameter space

Fast Inorganic Scintillators

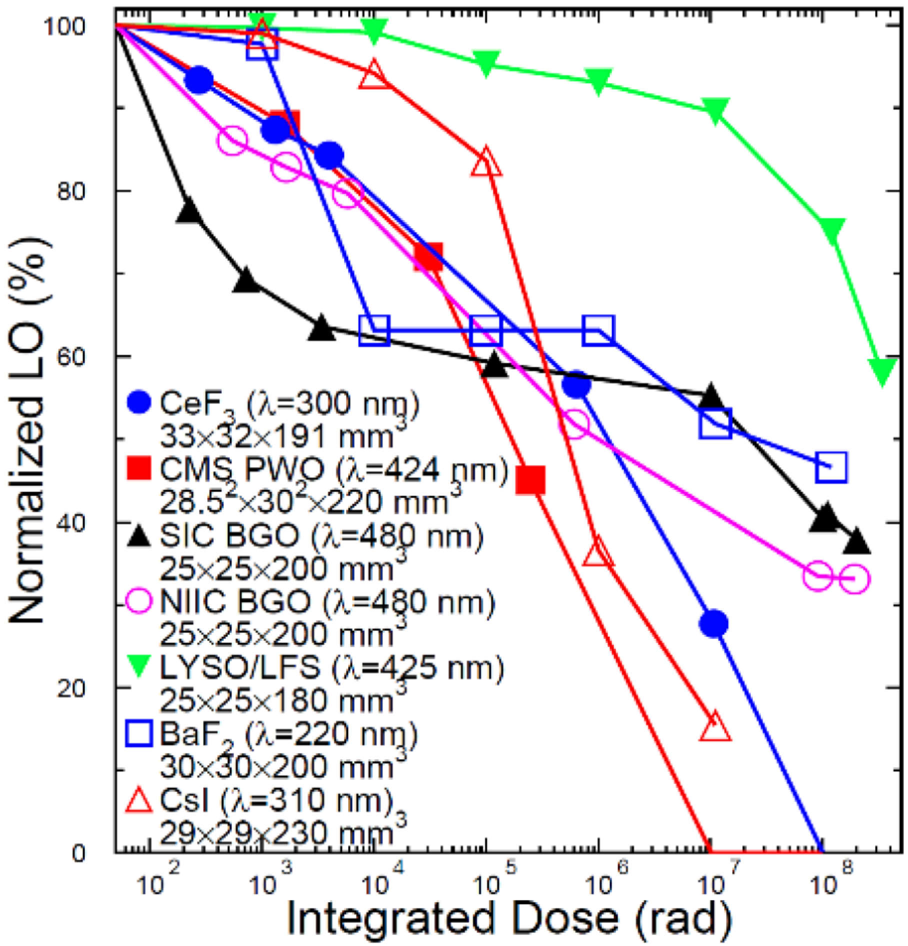
	GSO	YSO	LSO/ LYSO	CsI	BaF_2	CeF_3	$CeBr_3$	$LaCl_3$	$LaBr_3$
Density (g/cm^3)	6.71	4.44	7.4	4.51	4.89	6.16	5.23	3.86	5.29
Melting point (°C)	1950	1980	2050	621	1280	1460	722	858	783
Radiation Length (cm)	1.38	3.11	1.14	1.86	2.03	1.7	1.96	2.81	1.88
Molière Radius (cm)	2.23	2.93	2.07	3.57	3.1	2.41	2.97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

Radiation hardness

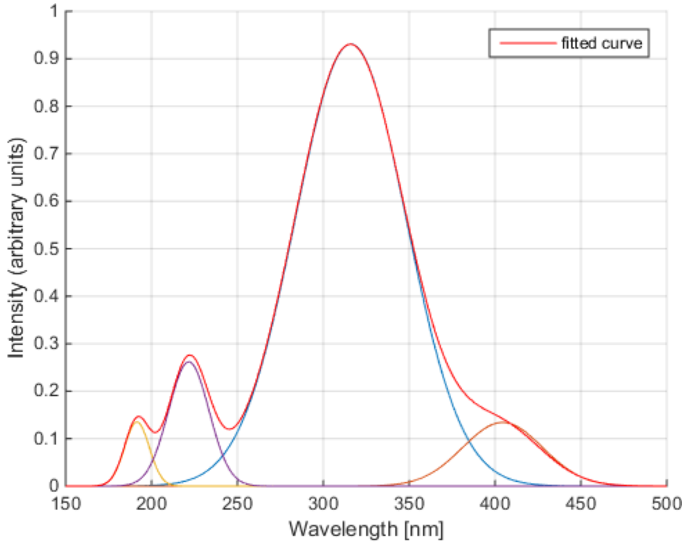


R.Y. Zhu

For radiation hardness, the leading candidates are BaF_2 and LYSO

Photosensor options for BaF_2 readout

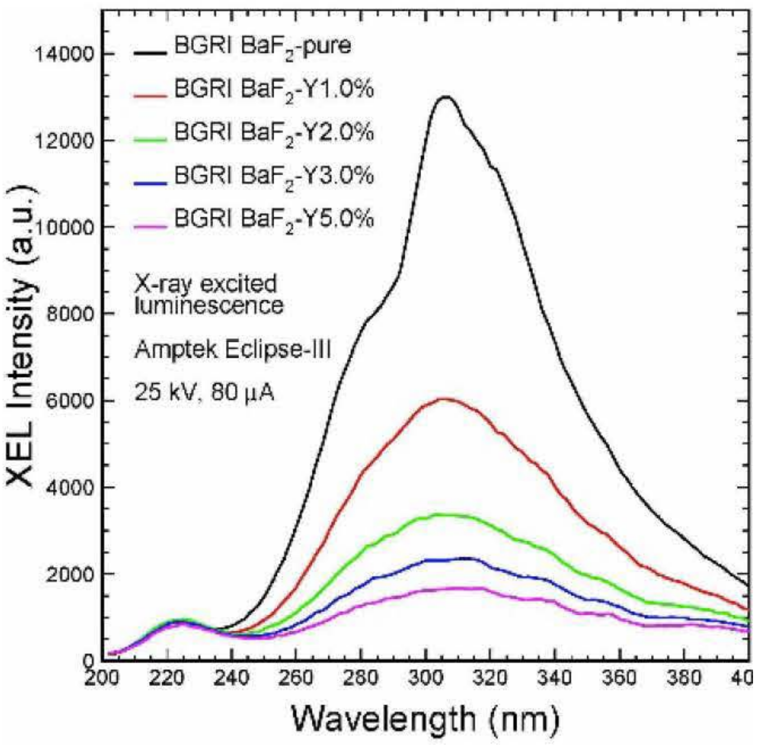
- Among the crystal choices, BaF_2 stands out
- BaF_2 has long been identified as an excellent choice for a Mu2e (II) calorimeter, provided that one has a way of utilizing the 220 nm fast component without undue interference from the 320 nm slow component
- There are actually two fast components ($\tau < 1$ ns) at 195 and 220 nm and two slow components ($\tau = 630$ ns) at 320 and 400 nm



- Viable approaches:
    - Directly suppress the slow scintillation component
    - Interpose an external filter
    - Use a photosensor that is sensitive only to the fast component
- Suppression of the BaF_2 slow component by Y doping, as developed by Zhu *et al.*, is a major advance, although quite a bit of R&D remains
    - Is the resulting fast-to-slow component amplitude ratio already sufficient to meet the rate and time resolution requirements of Mu2e-II?

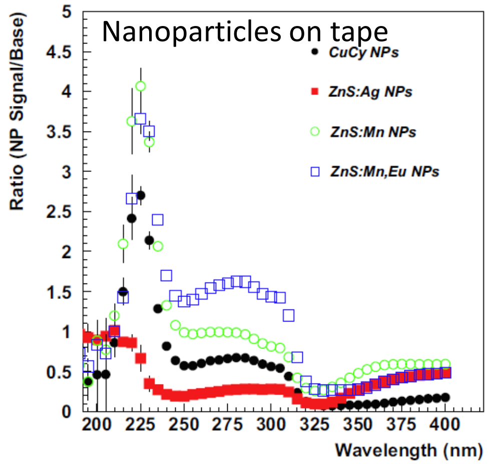
Using the fast component of BaF_2

- Zhu *et al.* have shown that the BaF_2 slow component can be suppressed by Y doping, with little effect on the fast component
  - This is a major advance
  - Work remains to study uniformity of Y doping and find a concentration plateau, as well as explore the radiation hardness



Photosensor options for Y-doped BaF_2

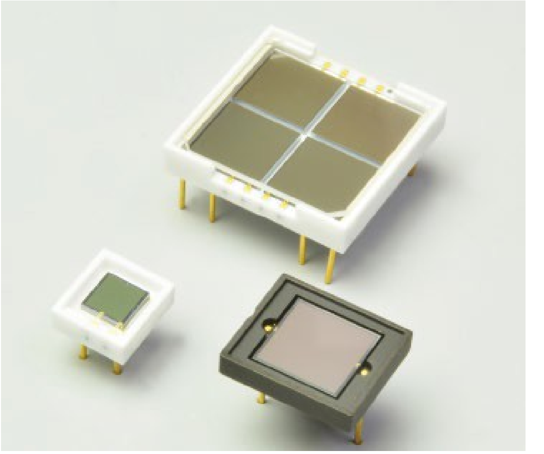
- We still lack an ideal photosensor for the rates of Mu2e-II
- What is required of an appropriate photosensor?
    - Spectral sensitivity in the 200 nm region for best energy and time resolution
    - Fast/slow component discrimination for high rate capability
    - Improved rise/fall time characteristics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

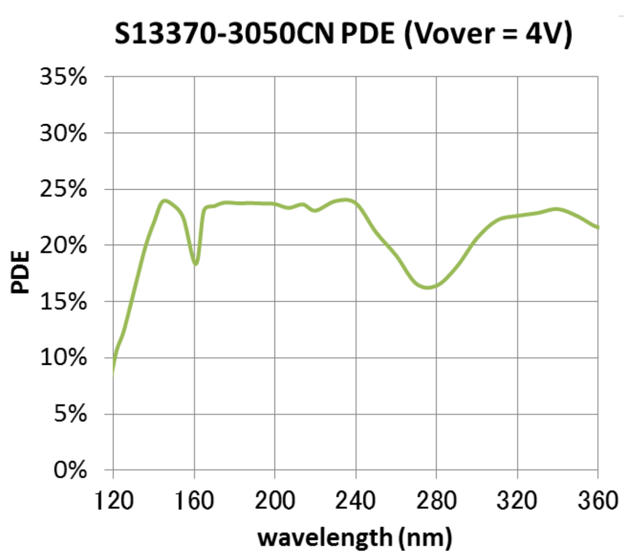


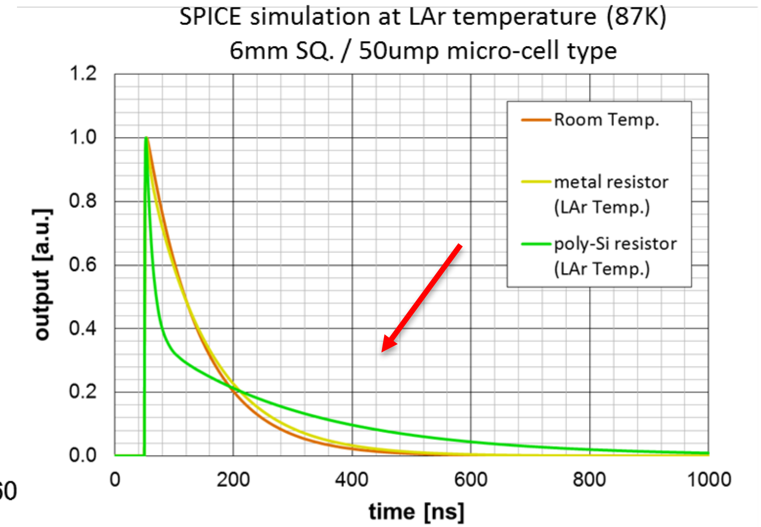
Hamamatsu VUV MPPC

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





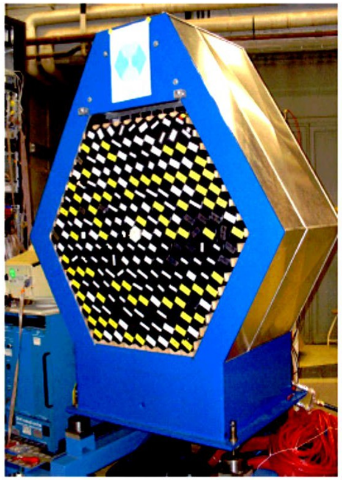


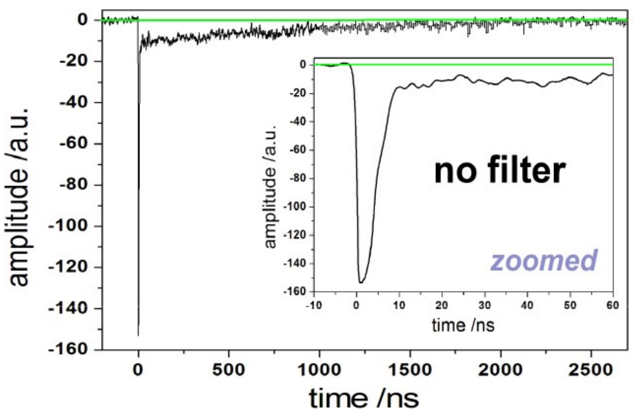
Series/parallel connection of 6x6 mm SiPMs, as in the current Mu2e calorimeter, improves decay time characteristics

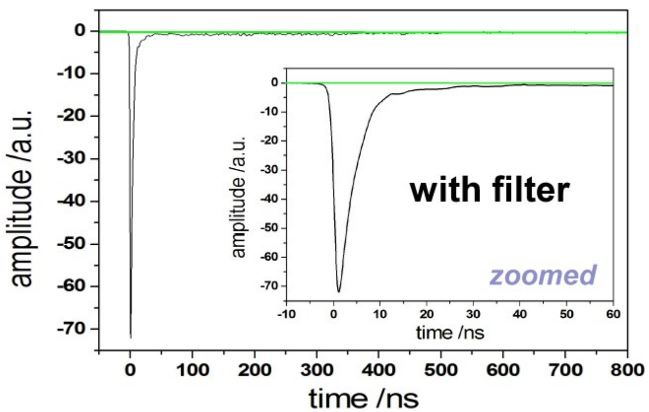
- FBK also has excellent VUV SiPMs

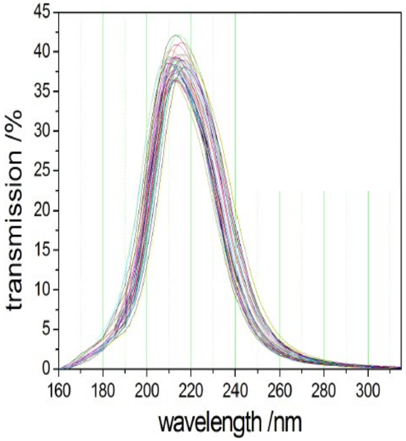
PMT + external filter

- 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

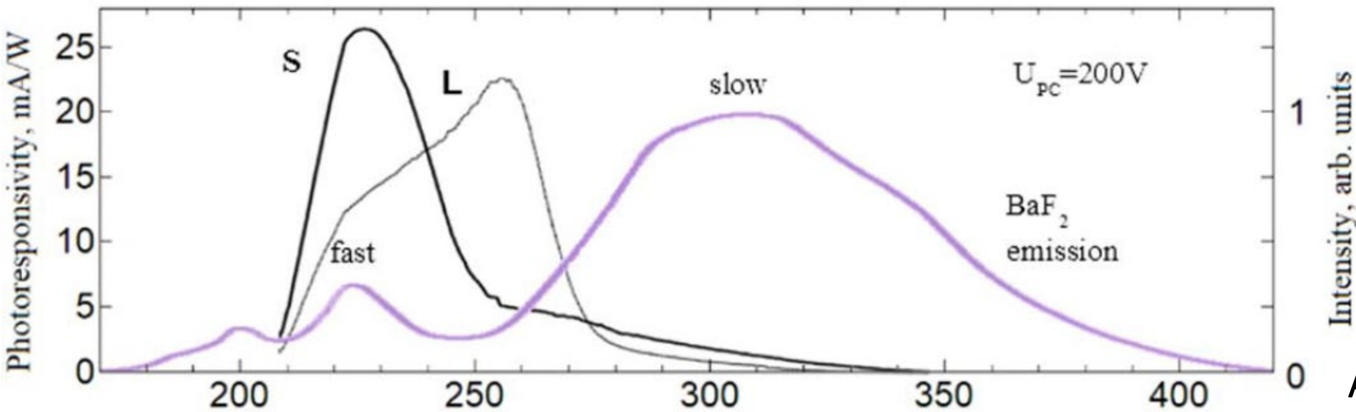
- The LAPPD, a channel plate PMT that works in a magnetic field, is very fast and potentially very attractive, but a great deal of R&D remains before we have practical device for use with BaF_2

    - 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

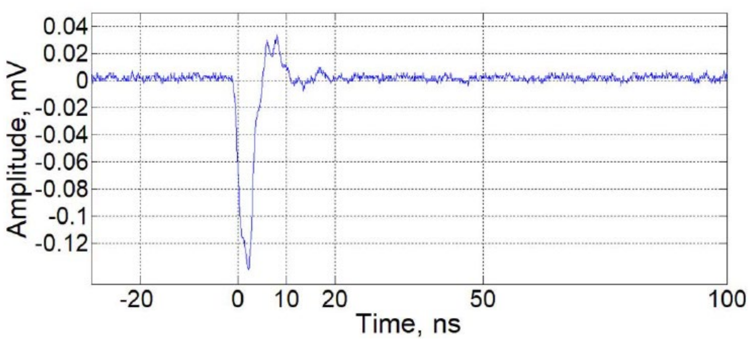
    - DH and RYZ had initiated an effort with ANL to develop an 8x8 cm LAAPD with a Cs_2Te UV-extended solar-blind photocathode
        - After preliminary discussions, this effort has been suspended

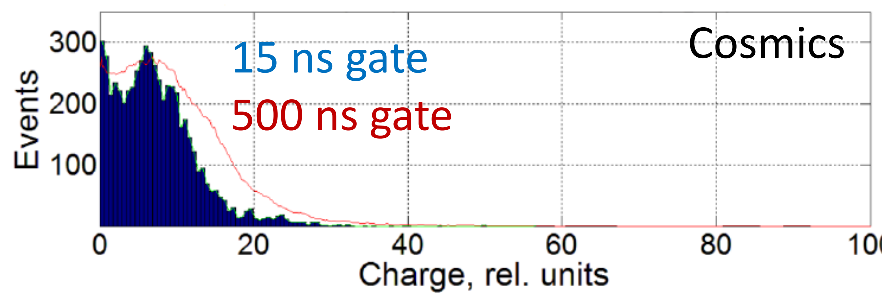
AlGaN photocathodes for an MCP

- 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.

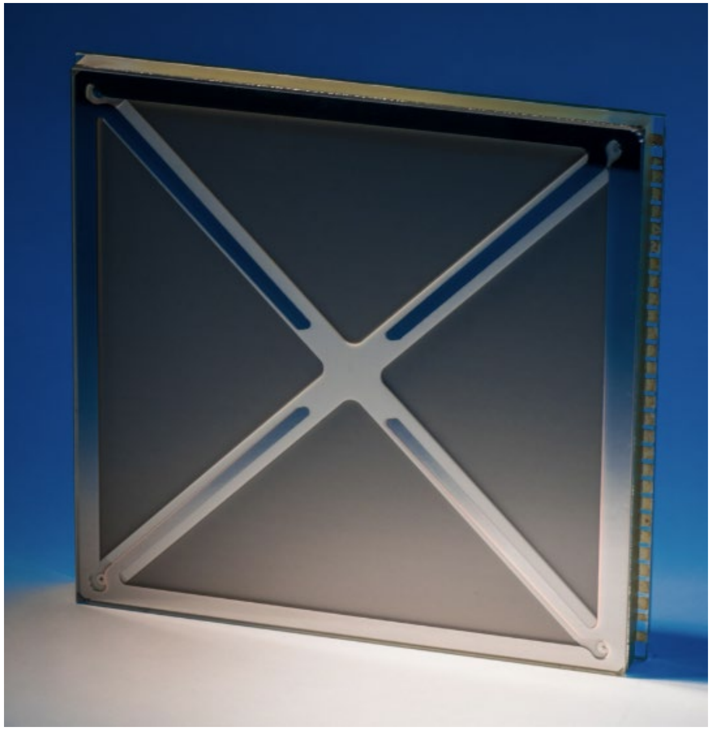




What is the lifetime in total charge at the anode of the MCP?

LAPPD with solar blind photocathode

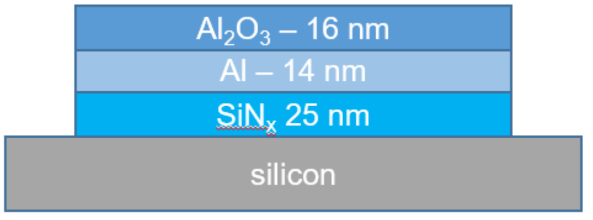
- The LAPPD, a channel plate PMT now produced by Incom in 20x20cm size, is very fast and potentially very attractive, but much R&D remains before we have a practical device for use with BaF_2
  - Quartz entrance window
  - Cs-Te or AlGaN photocathode
  - A size appropriate to the scintillating crystal Molière radius
  - An affordable price



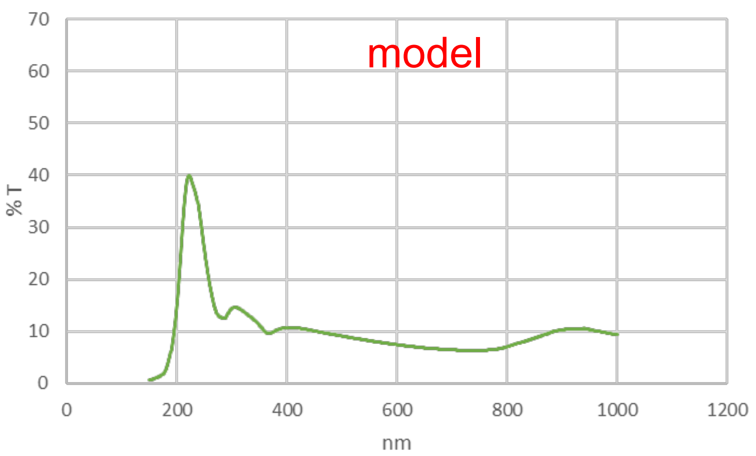
An abortive attempt to develop such a device using existing equipment was launched by ANL/Caltech, but was killed when ANL HEP Division management changed

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

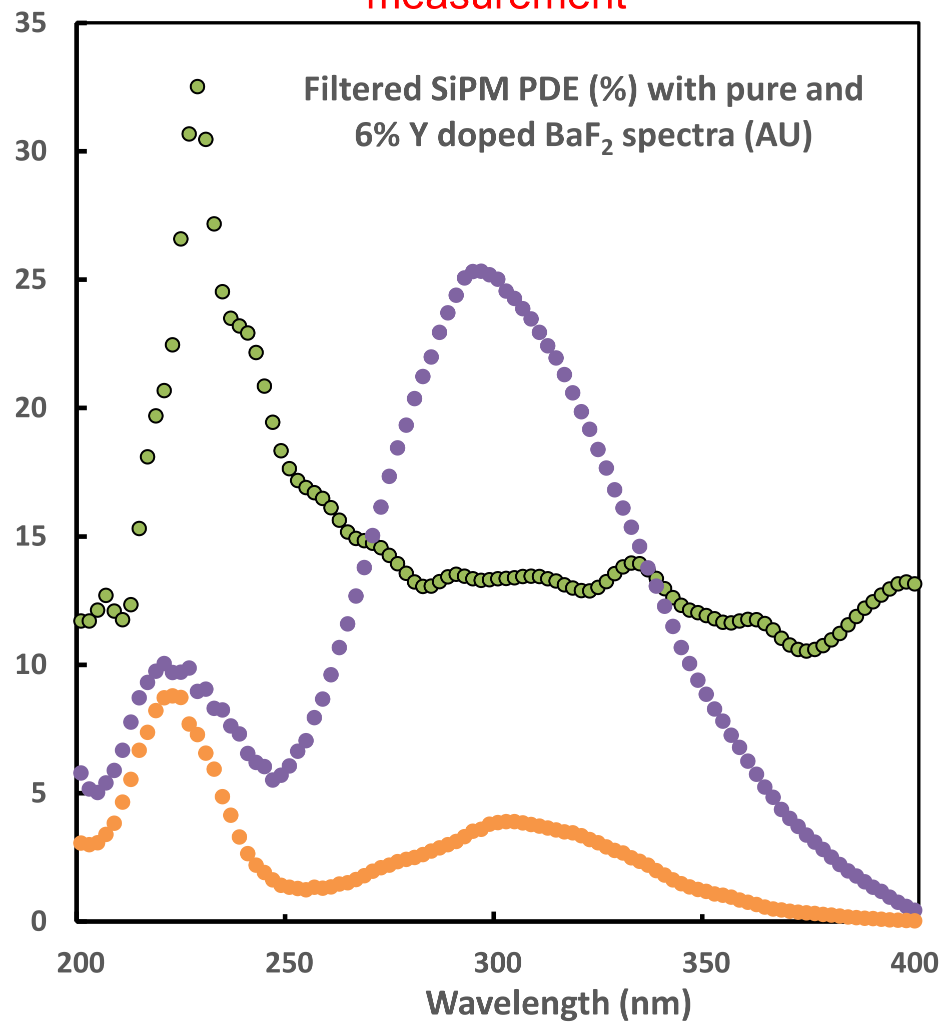
FBK SiPM with three layer filter



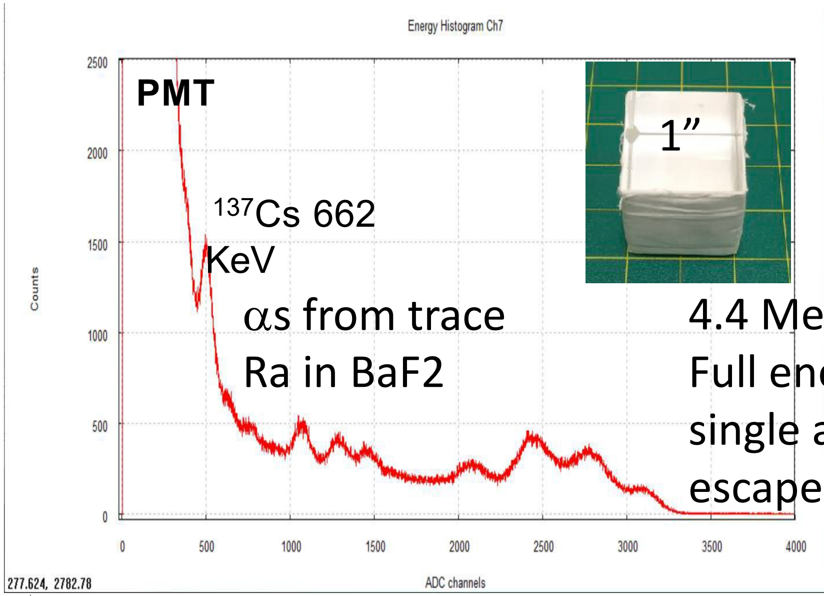
Wafer 11

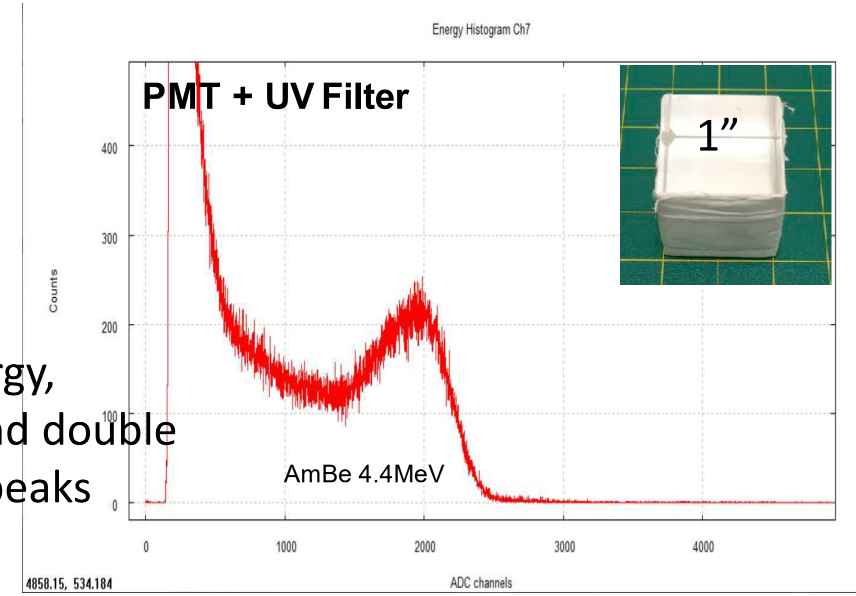


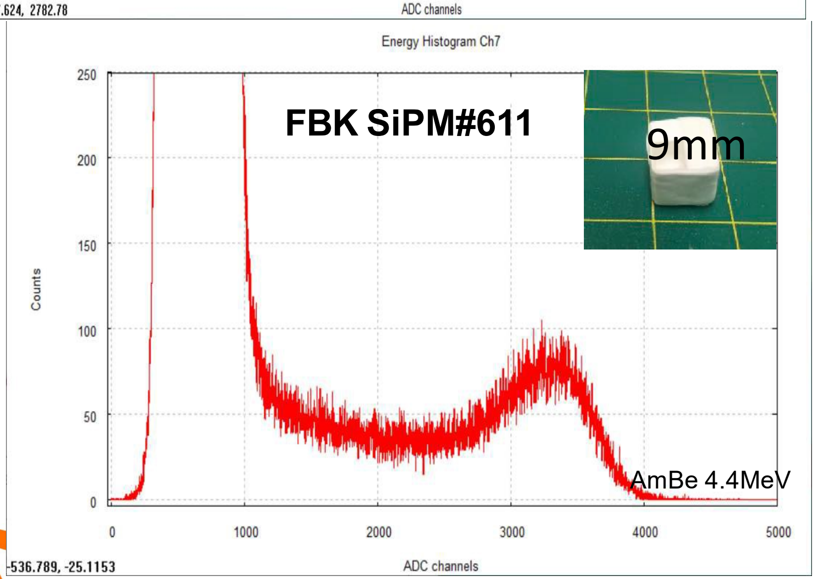
measurement



BaF_2 + AmBe Read out by PMT and FBK#611

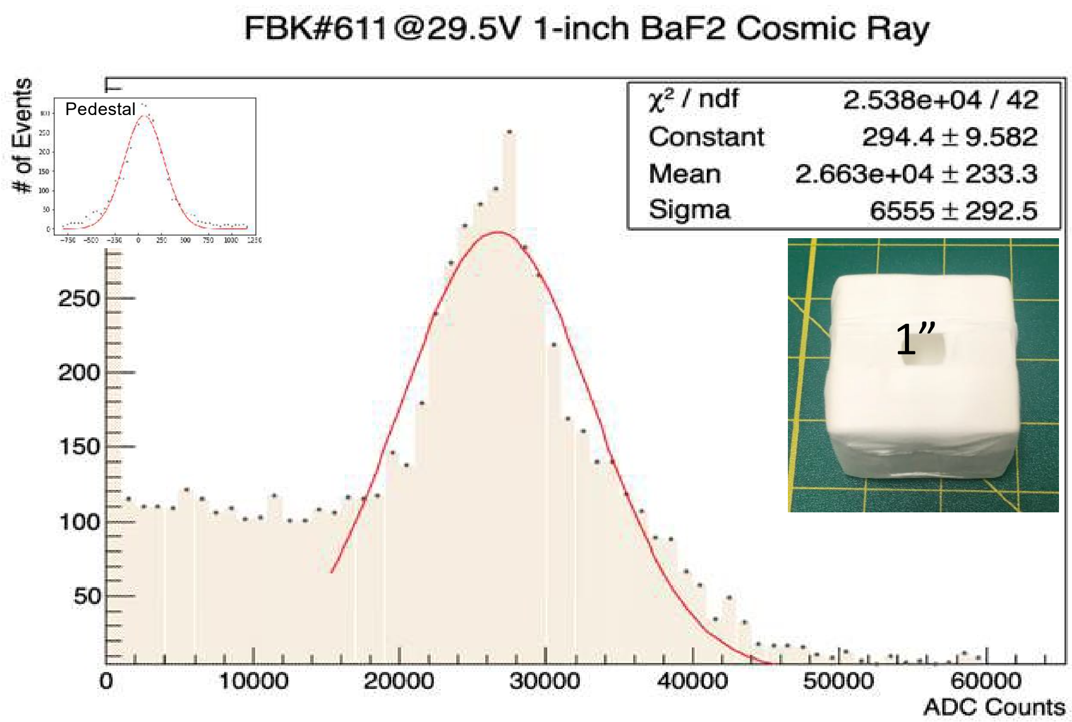






- An AmBe neutron source emits copious 4.4 MeV gammas
- FBK SiPM #611 operated at 29.5V
- BaF_2 dimension 9 x 9 x 9 mm, wrapped with teflon with an opening of 6x6 mm
- 3400 (adc)/29.1(pe/adc) = 117 pe
- 117 pe / 4.4 MeV = 27 pe/MeV

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

Conclusions

- A very fast barium fluoride crystal calorimeter that exploits the fast scintillation component for its high rate capability and excellent time resolution is an appropriate component of a Mu2e-II upgrade or other high rate experiments
- Y-doped BaF_2 provides very significant suppression of the 300 nm slow component with little effect on the 220 nm fast component
- In order to fully exploit the 0.6 ns decay time of the fast component for improved rate capability and time resolution, better photosensors are required and several are under development
- Desired device characteristics
  - High QE for the 220nm BaF_2 fast component
  - Insensitive to the 320nm BaF_2 slow component
  - Excellent rate performance
  - UV stability
  - Radiation hard to γs and neutrons

Status

- The LOI draft has been circulated to the calorimeter listserv
  - Some edits have been received
  - Some authorship requests have been received
    - Deadline will be midnight PDT on August 30, to allow time to coordinate submission with the main LOI on August 31

- A Calorimeter Workshop is scheduled for September 22 at 8AM PDT
  An Indico page is in preparation

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