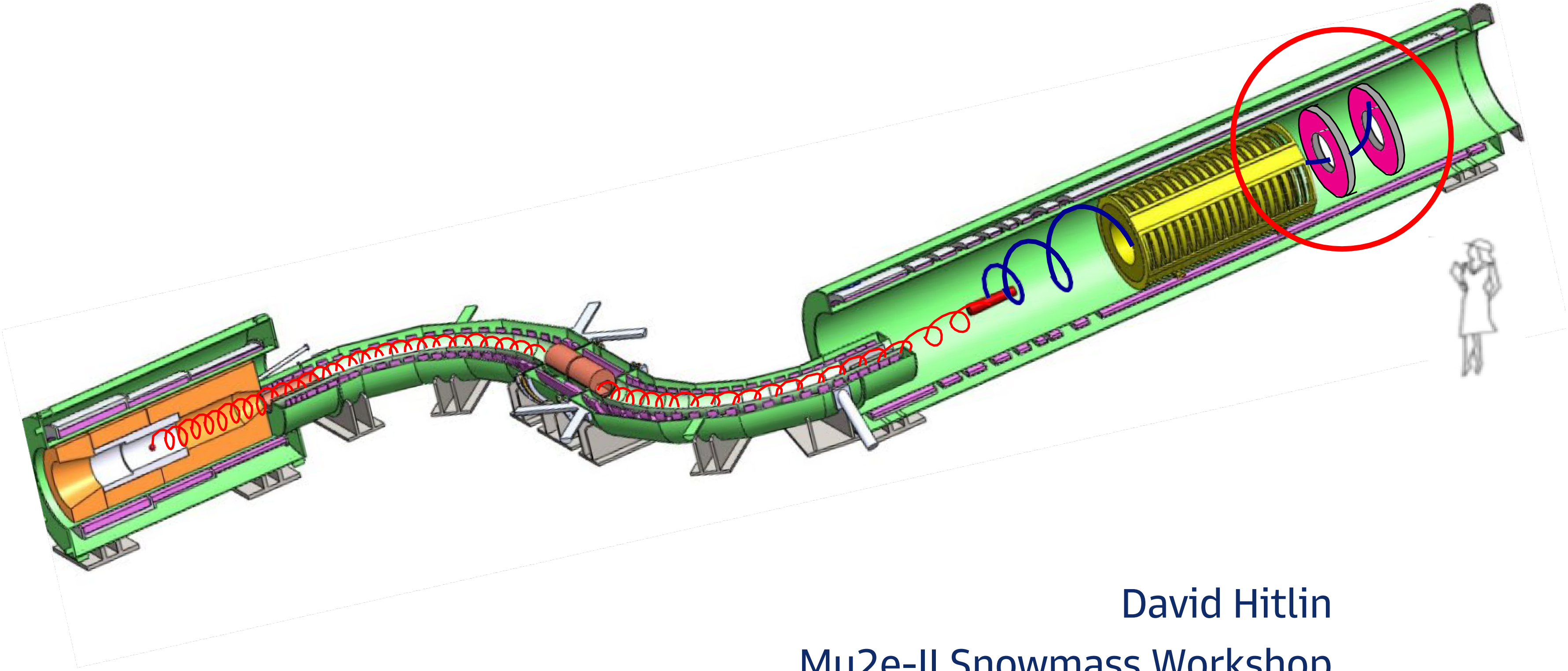
Status Report
Mu2e-II Snowmass21 Calorimeter Group



David Hitlin

Mu2e-II Snowmass Workshop

October 28, 2020

Frank's 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 every 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."

The nominal situation

Mu2e Calorimeter Requirements

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

• Energy resolution	$\sigma < 5\%$ (FWHM/2.36) @ 100 MeV
• Time resolution	$\sigma < 500$ ps
• Position resolution	$\sigma < 10$ 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	

PIP-II/Mu2e-II: higher rates (~x3) and duty factor from and correspondingly higher ionizing radiation (**10 kGy/yr**) and neutron levels (**10^{13} n_1 MeV equiv/cm^2 total**), which are particularly important at the inner radius of disk 1

Nominal Mu2e-II Calorimeter Requirements

There will be higher rates, neutron flux and 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

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

David Hitlin Mu2e-II Workshop - Calorimeter October 28, 2020

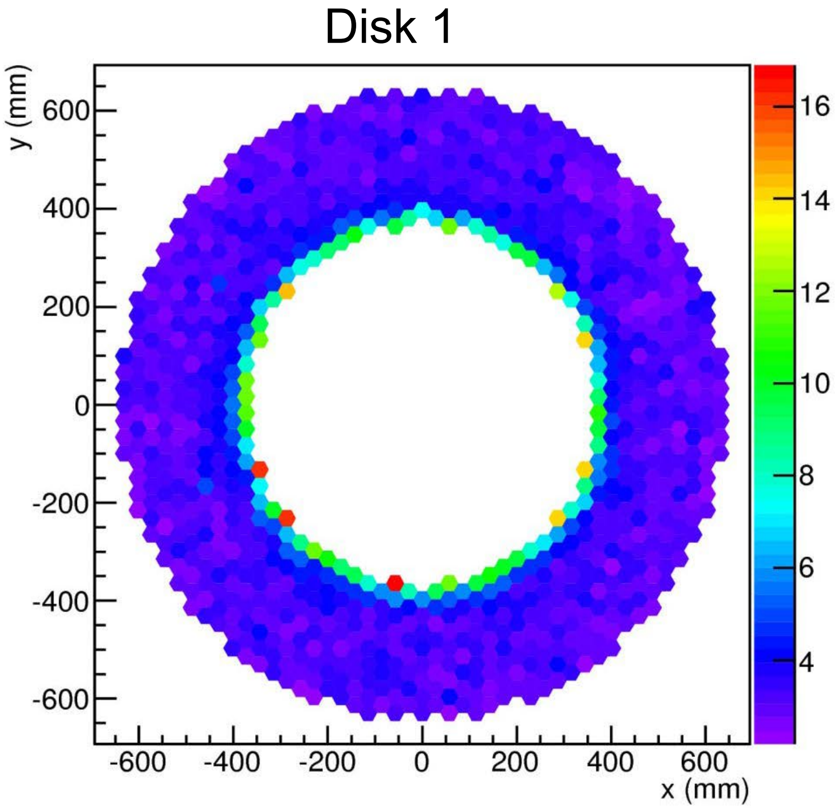
The resulting radiation environment

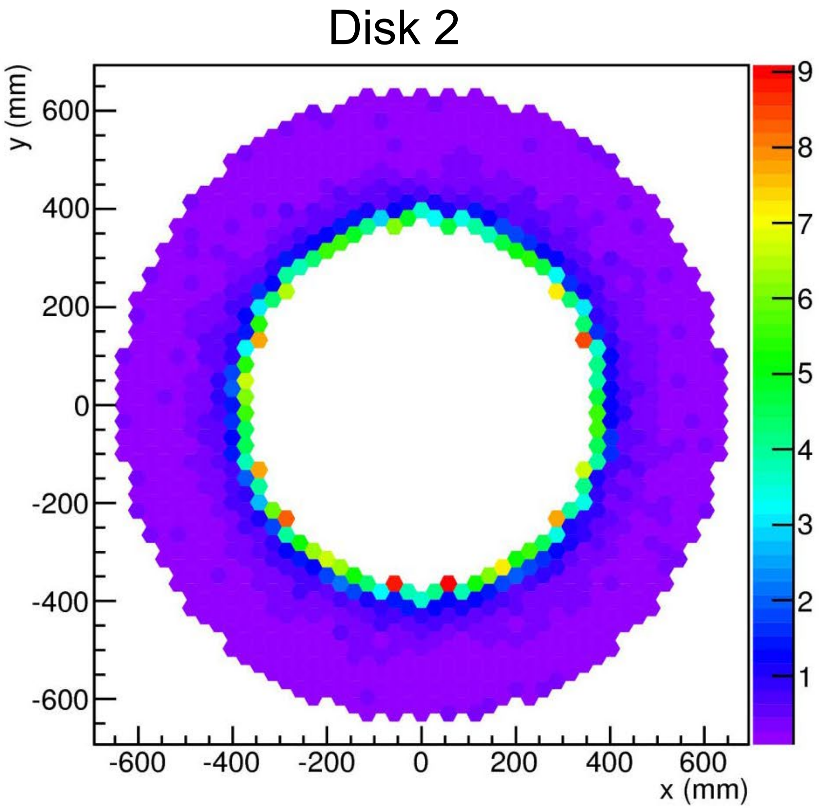
Frank’s challenge corresponds to

- 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),

The worst situation is at the inner radius of disk 1, but radial falloff is not extreme
Disk 2 dose is substantially lower

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

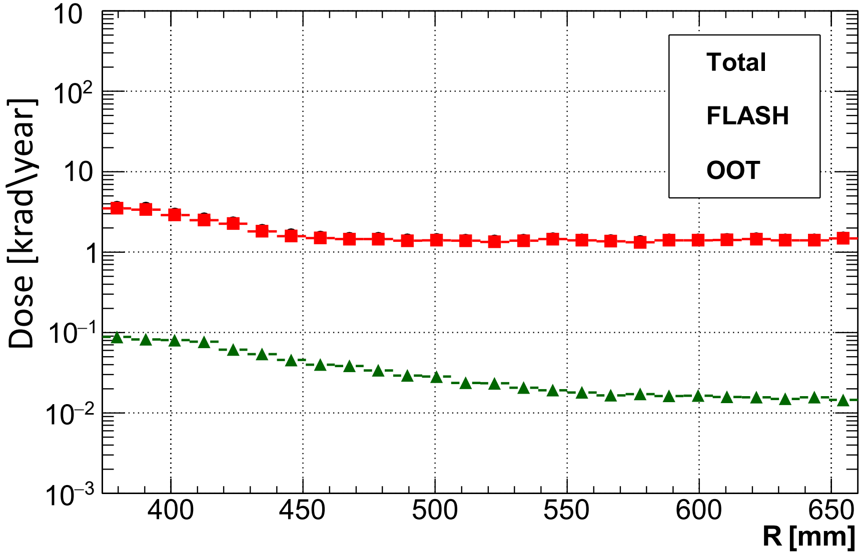
Echenard

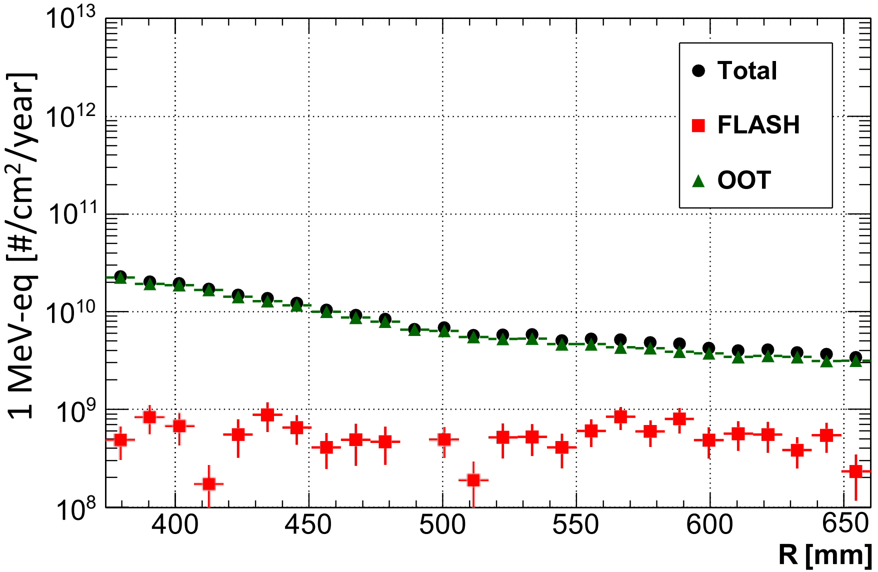
Mu2e

γ Dose crystals

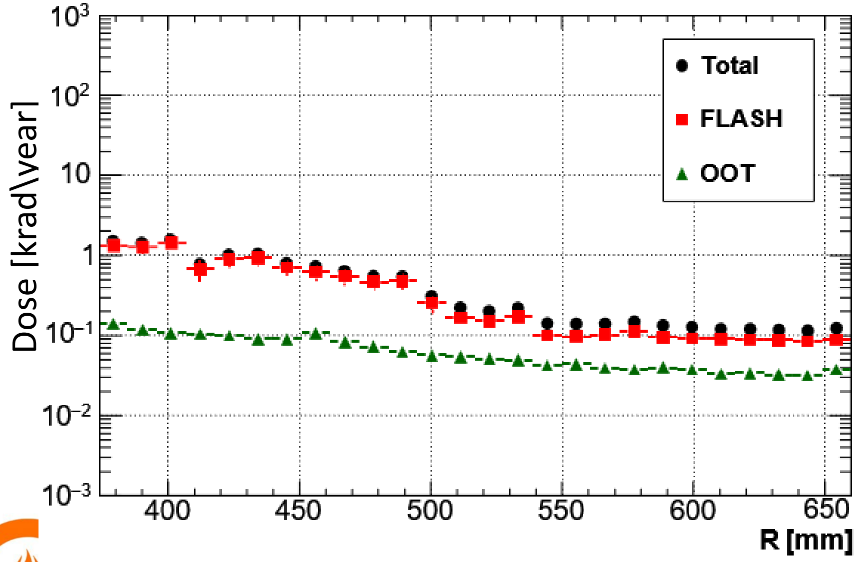
Neutron flux SiPMs

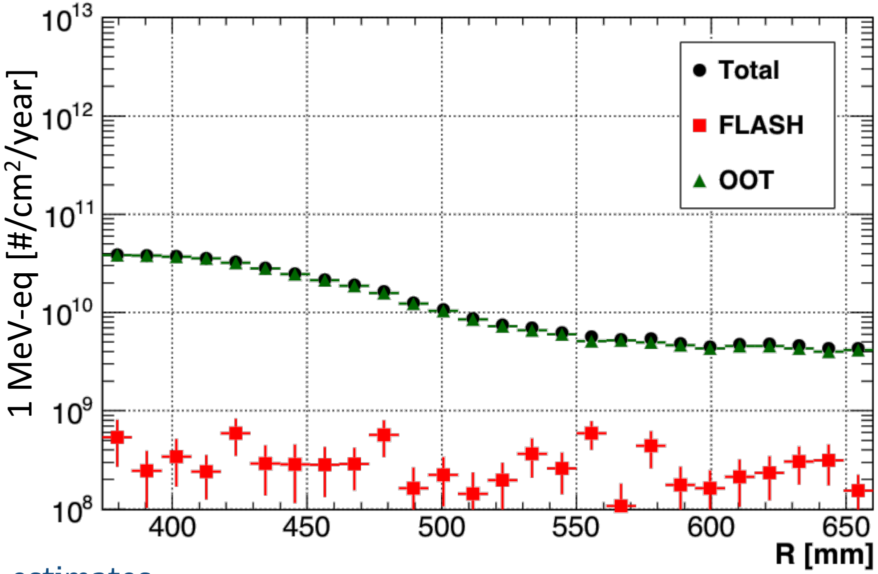
Disk 1





Disk 2

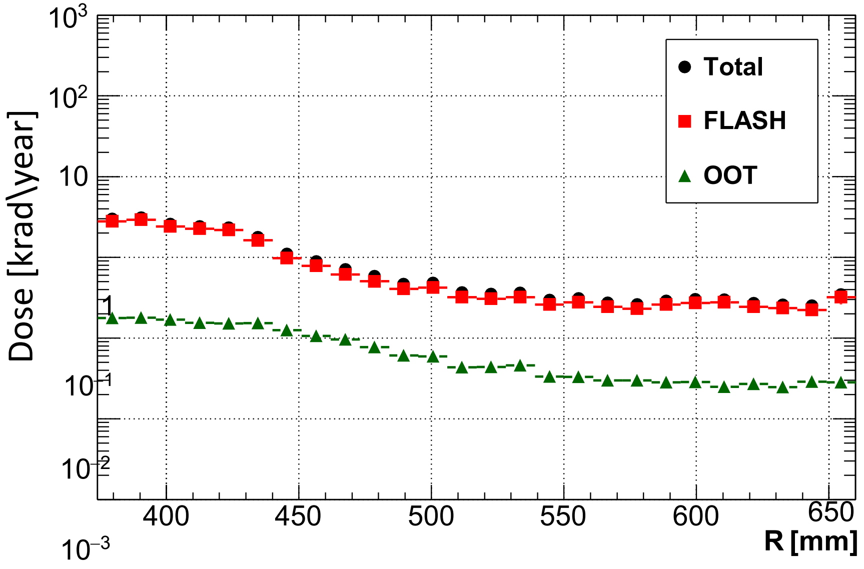


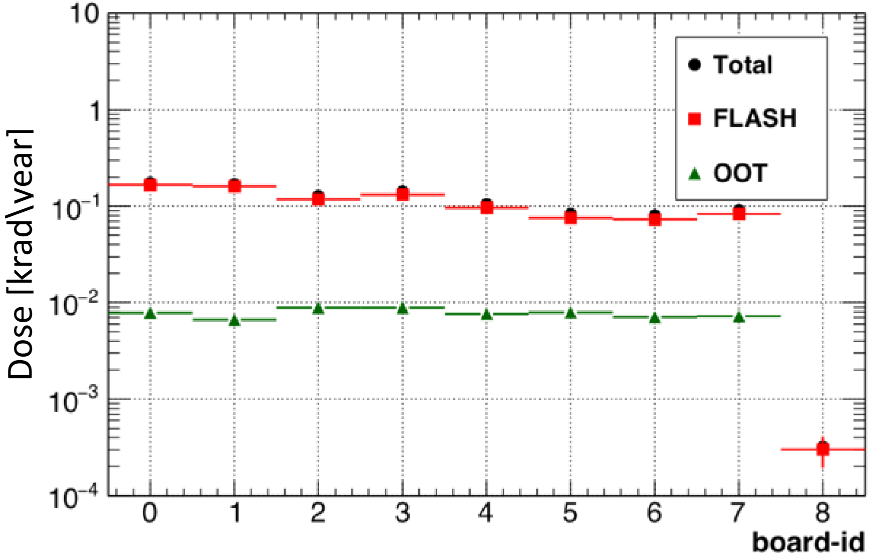


S.Giovannella MDC 2018 updates on calorimeter dose estimates

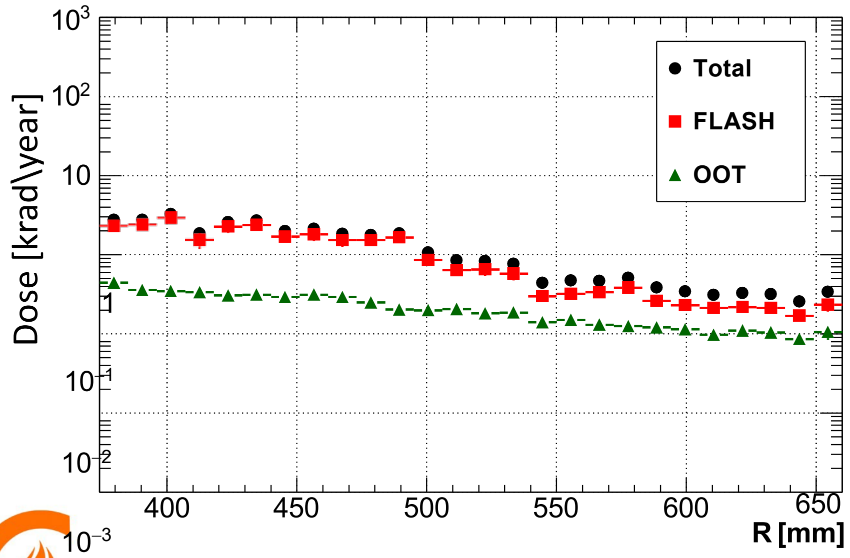
γ Dose – FEE   γ Dose – Dirac

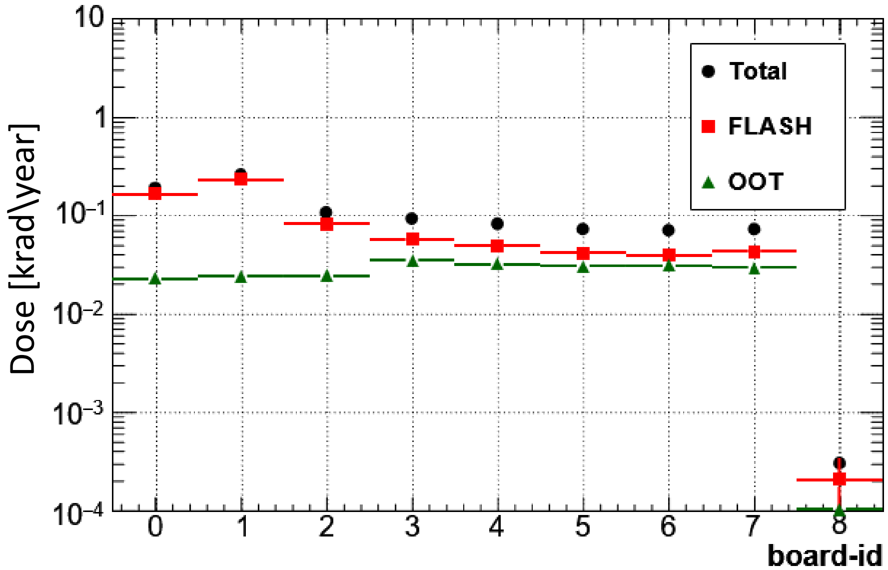
Disk 1





Disk 2





S.Giovannella MDC 2018 updates on calorimeter dose estimates

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.

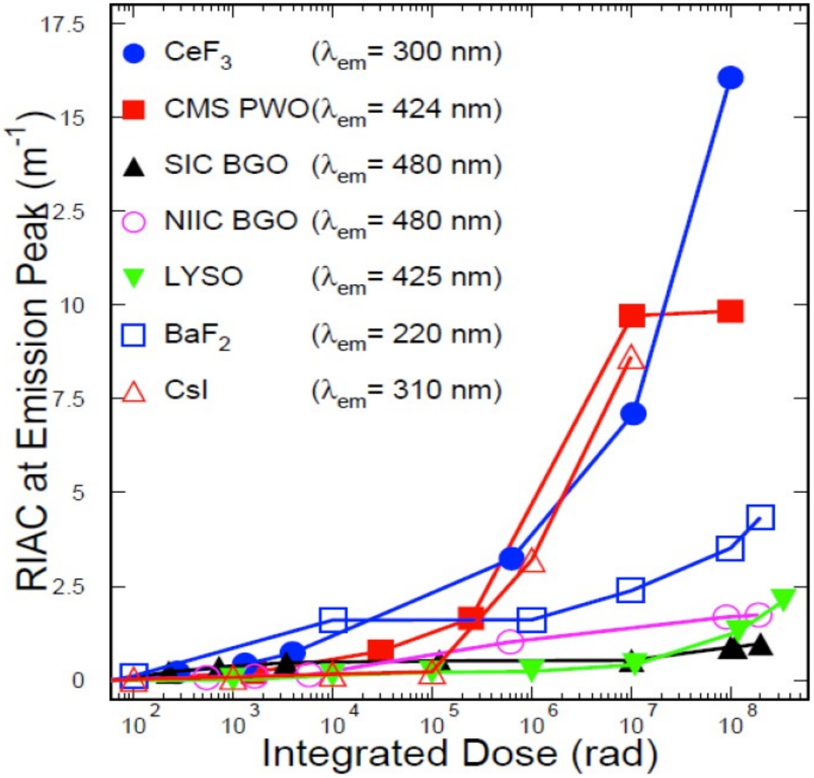
c. Relative light yield normalized to the light yield of LSO

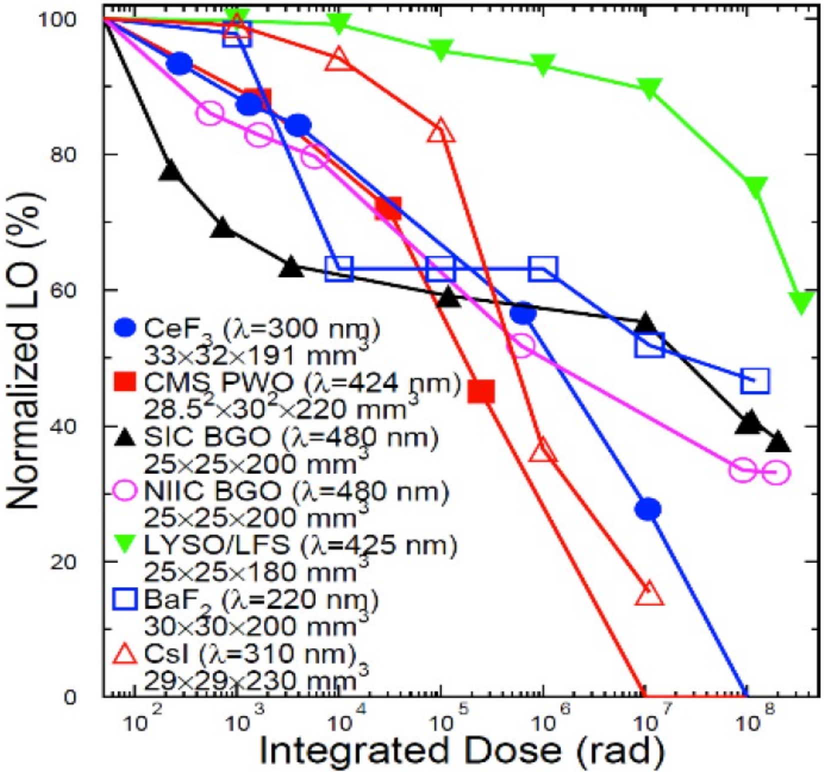
d. At room temperature (20°C) #. Softening point

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

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

Radiation hardness 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

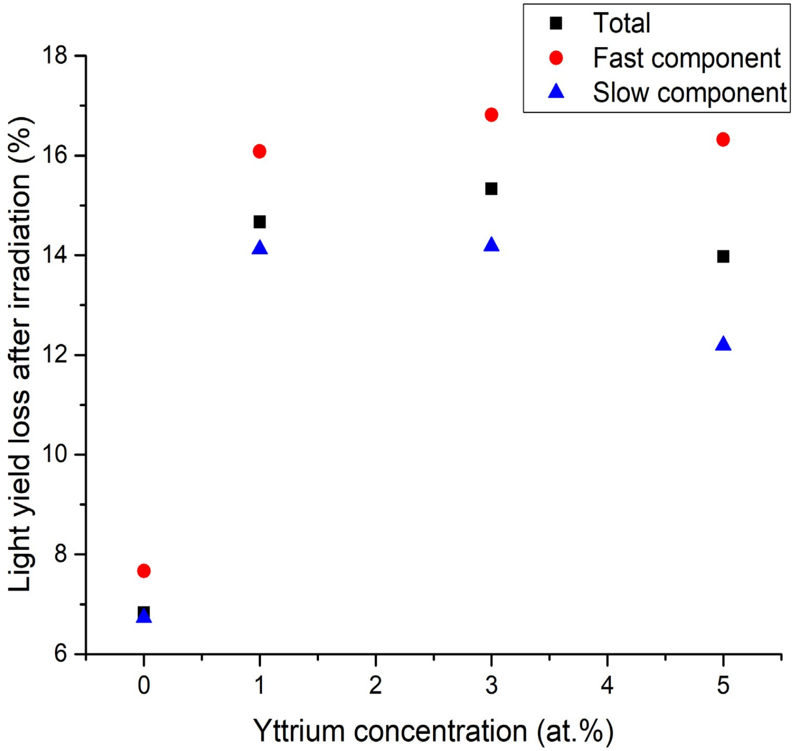
- Caltech plans to study the light output change of BaF_2(Y) under γ irradiation
  Dubna has done tests with reactor neutrons up to ~2.3×10^{14} n/cm^2 with BaF_2(Y) samples from SICCAS and BGRI
- In unirradiated samples, the slow signal is suppressed 3.6 times in the 1at.% doped sample, 7.2 times in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

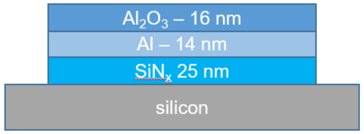
Y doping	0%	1at.%	3at.%	5at.%
Unirradiated	**526**	146	71	67
Irradiated	490	125	60	58
LO_{Irr}/LO_{Unirr}	0.93	0.856	0.845	0.866

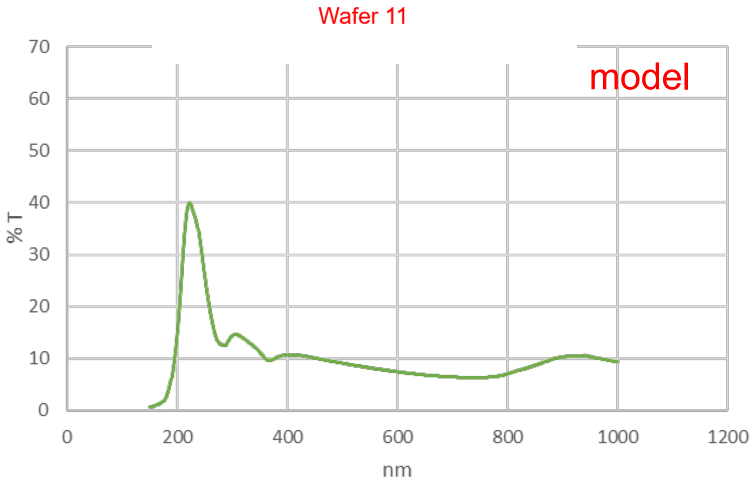


Y. Davydov

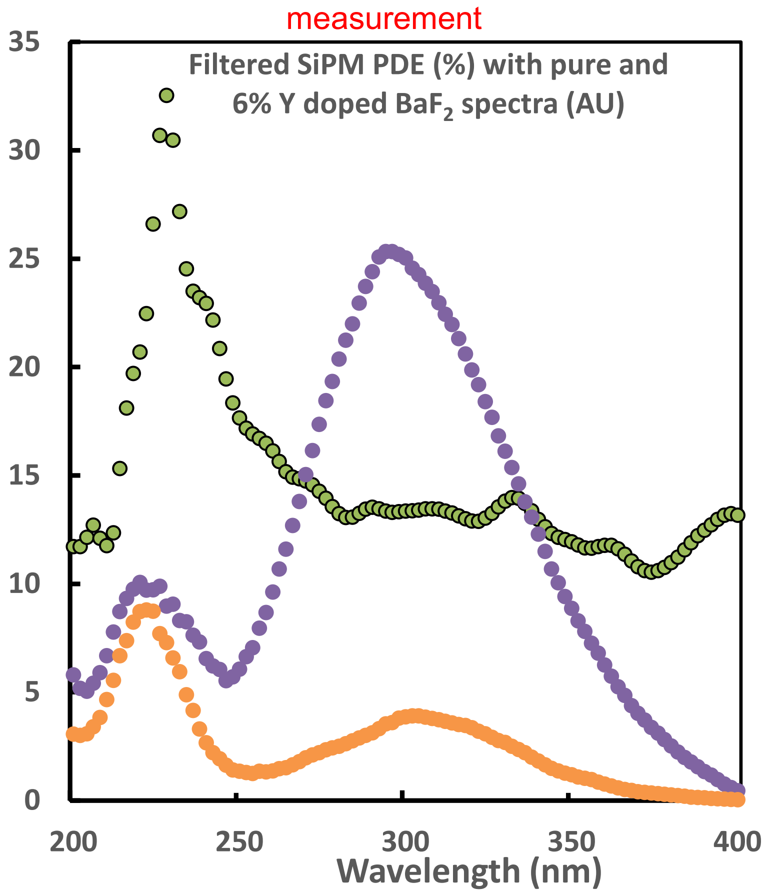
Photosensor

- 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





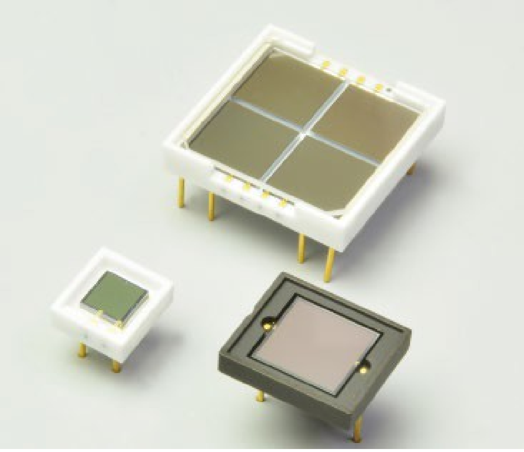
- Neutron dose is the largest concern
  - Reduced temperature operation is the response
- Pulse shaping will be required

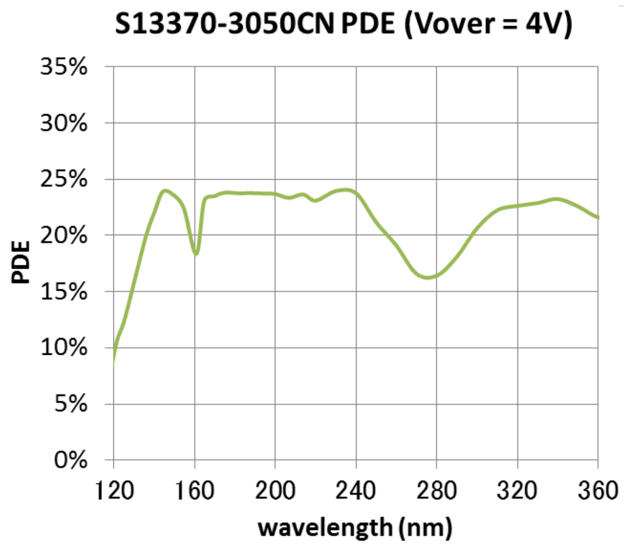


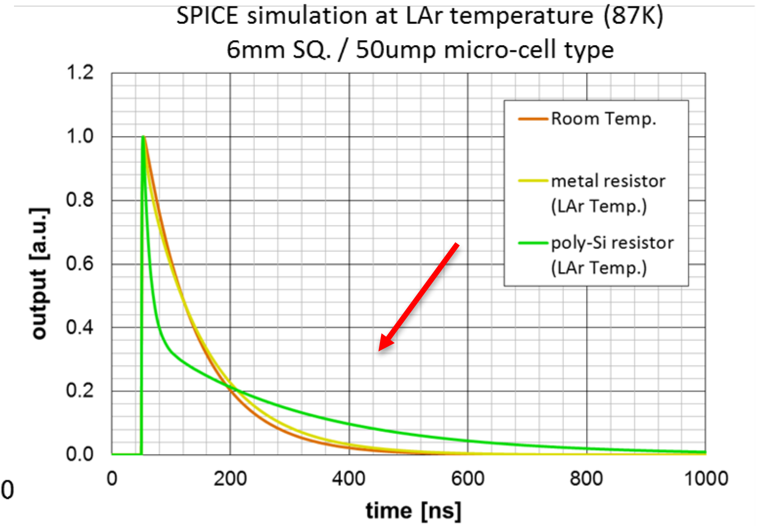
Hamamatsu VUV MPPC

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

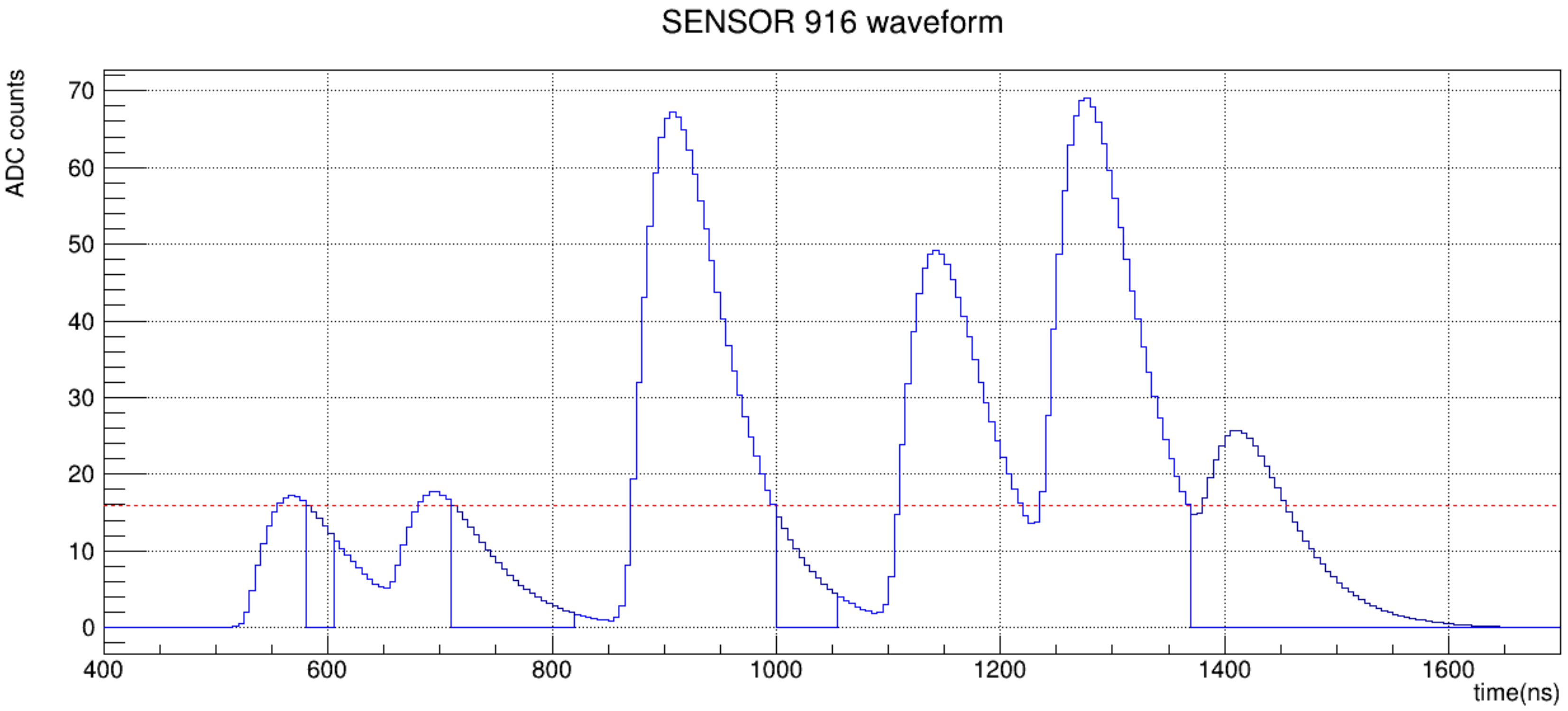
Mu2e

- 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

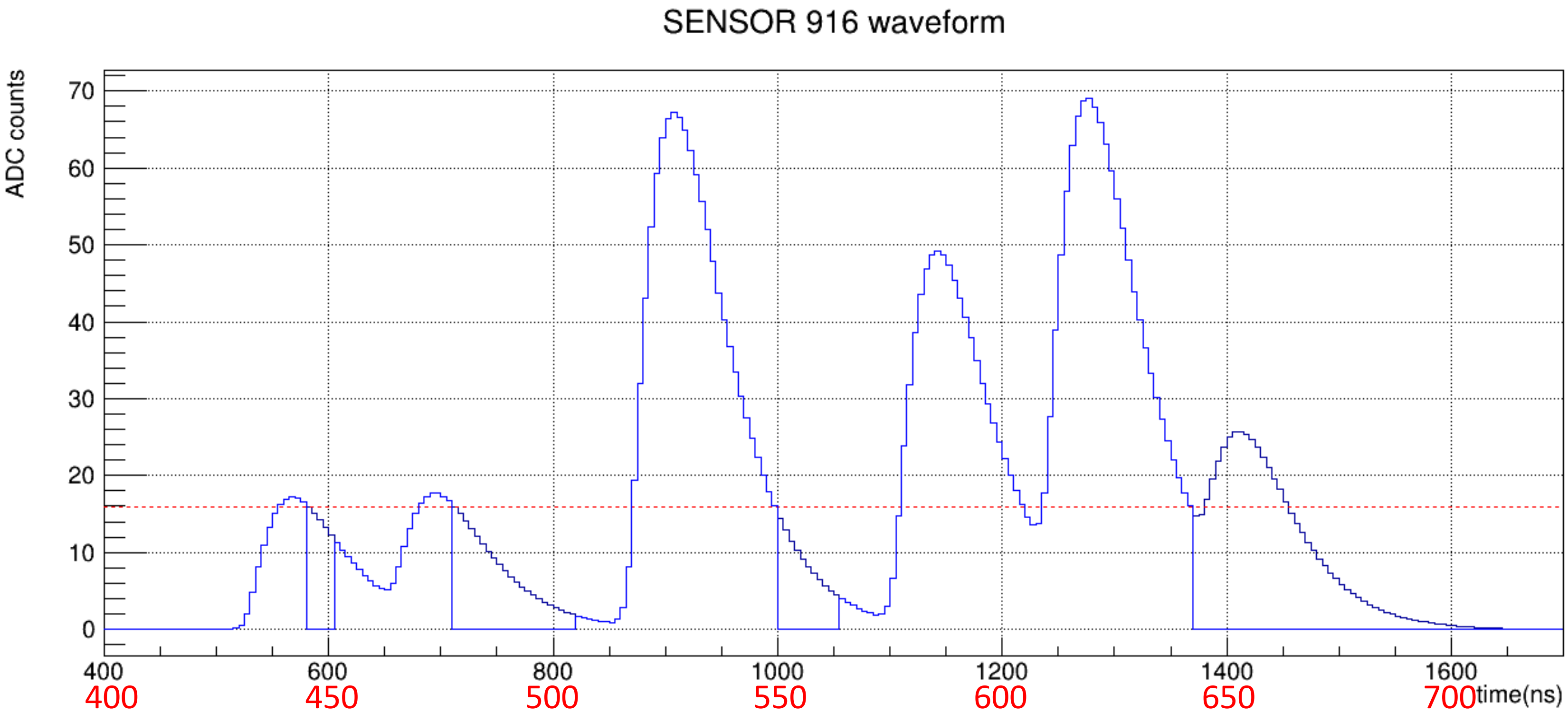
- ☐ Current Mu2e ecal event (simulation, 1 channel, inner ring, crowded ...)



- 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 is challenging at a Megarad
  - 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

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