The Mu2e Calorimeter at CD1 and at Project X

Project X Summer Study

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The Mu2e Calorimeter at CD1 and at Project X

- The Mu2e calorimeter – requirements and realization
- The initial environment
- The Project X environment
- Prospects for coping
- Potential R&D directions

Mu2e Apparatus

Production Solenoid

- Production target
- Graded field

- Delivers ~ 0.0016 stopped μ^- per incident proton
- 10^{10} Hz of stopped muons

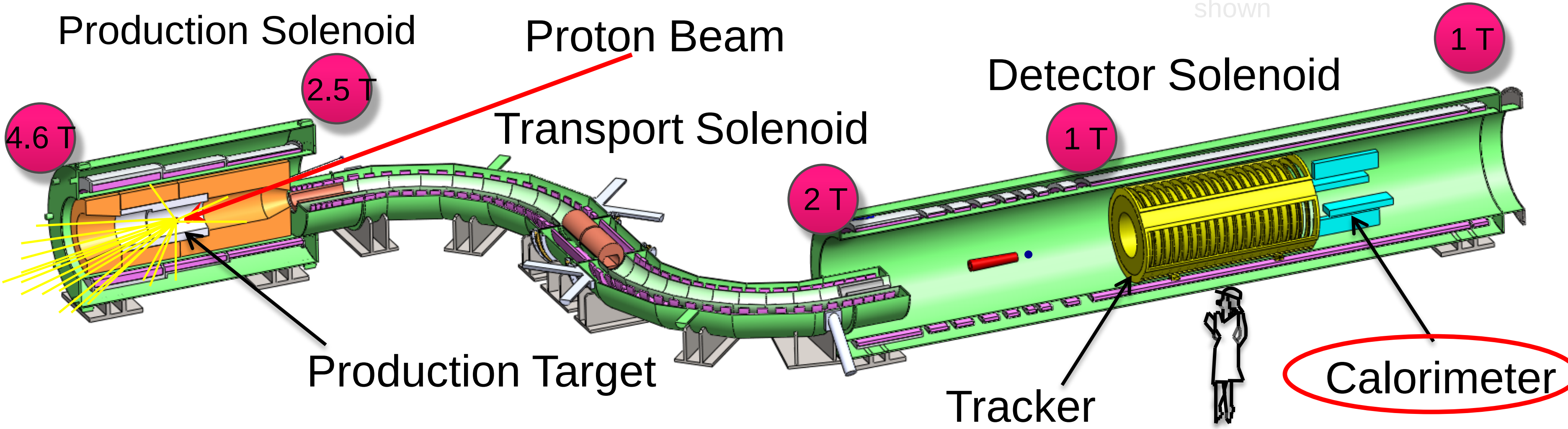
Detector Solenoid

- Muon stopping target
- Tracker
- Calorimeter
- Warm bore evacuated to 10^{-4} Torr

Transport Solenoid

- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator

Cosmic Ray Veto not shown

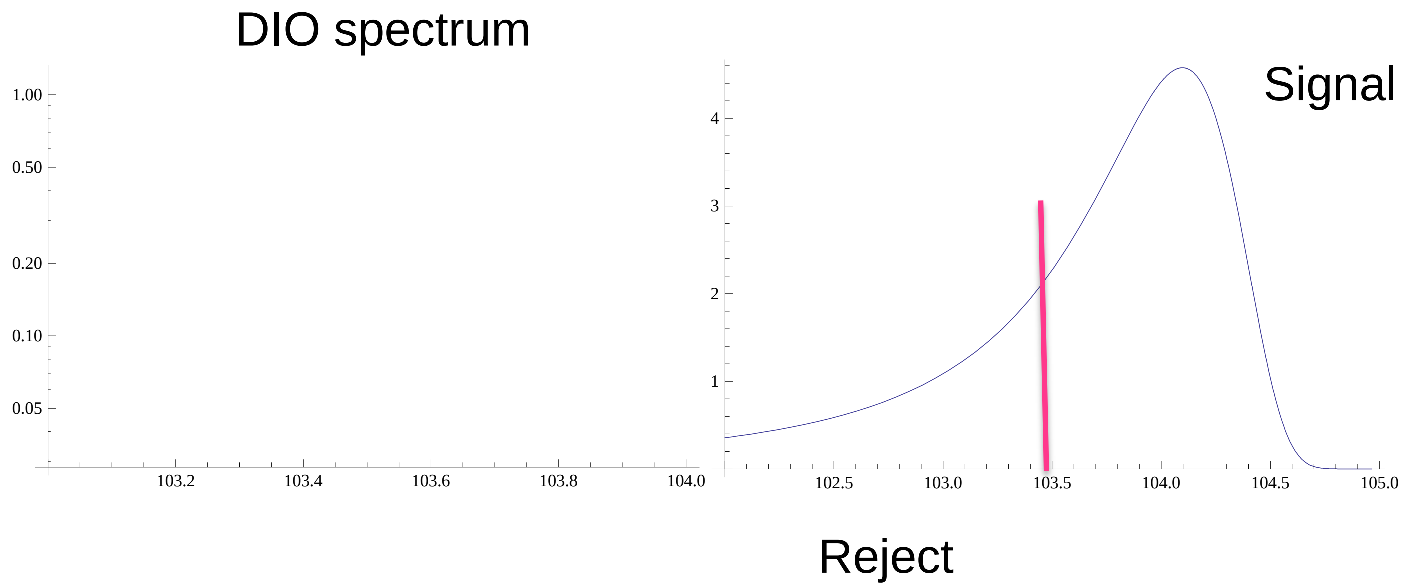


Calorimeter requirements

The purpose of the calorimeter is to confirm that a reconstructed track of a $\mu \to e$ conversion electron candidate is well-measured, and was not created by a spurious combination of hits in the tracker.

1. Measure the position of the conversion electron $\to \sigma(x) \leq \mathcal{O}(1\ \text{cm})$.
2. Compare the energy deposited in the calorimeter to the reconstructed track momentum $\to \sigma(E) \leq \mathcal{O}$ (2%), with an uncertainty in the energy scale small compared to the resolution.
3. Compare the time of the energy deposit in the calorimeter to the time determined from the tracker $\to \sigma(t)\ \mathcal{O}$ (≤1 ns).
4. Provide particle identification to separate, for example, electrons from muons.
5. Provide a trigger that can be used for event selection
6. Maintain functionality in a 50 Gy/year radiation environment with light yield loss < 10%

Excellent calorimeter resolution needed to reject DIO background



- Resolution requires the statistics of a scintillating device – crystal or LXe

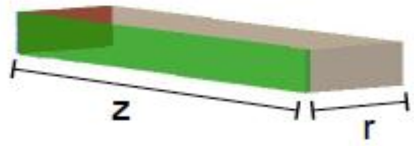
Fast, rad hard scintillating crystals

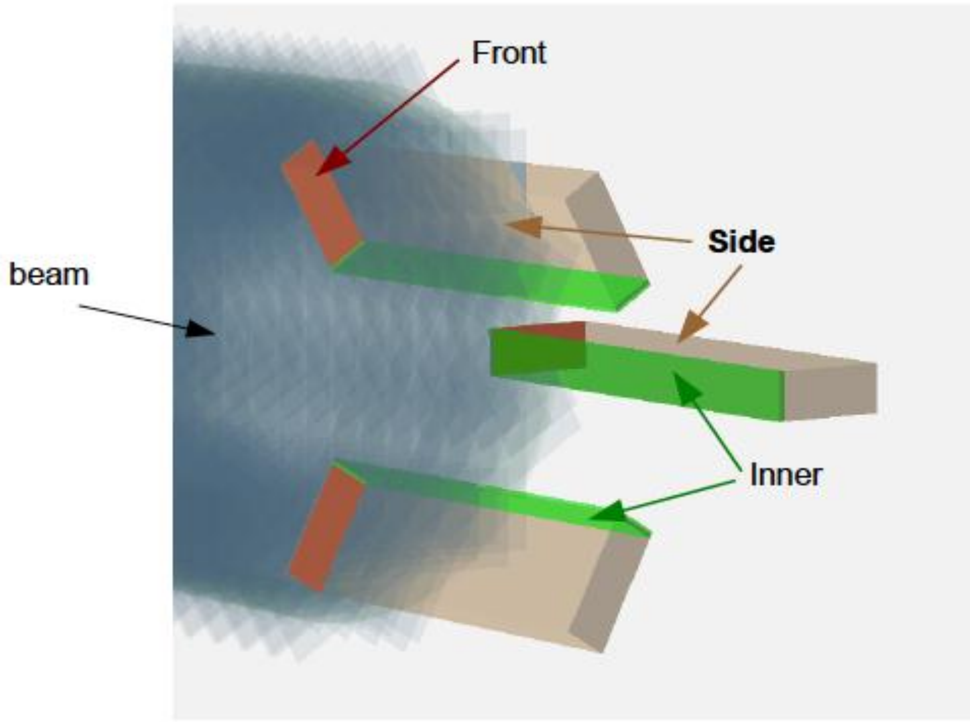
Crystal	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2	$LaBr_3(Ce)$	$LaCl_3(Ce)$
Density (g/cm³)	4.89	7.13	7.40	8.3	7.77	5.29	3.86
Melting Point (°C)	1280	1050	2050	1123	824	788	859
Radiation Length (cm)	2.03	1.12	1.14	0.89	0.93	1.88	2.81
Molière Radius (cm)	3.10	2.23	2.07	2.00	2.21	2.85	3.71
Interaction Length (cm)	30.7	22.8	20.9	20.7	21.0	30.4	37.6
Refractive Index [a]	1.50	2.15	1.82	2.20	1.82	1.9	1.9
Hygroscopicity	No	No	No	No	No	Yes	Yes
Luminescence [b] (nm) (at peak)	300 220	480	402	425 420	?	356	335
Decay Time [b] (ns)	650 0.9	300	40	30 10	?	20	570 24
Light Yield [b,c] (%)	36 4.1	21	85	0.3 0.1	?	130	13 42
d(LY)/dT [b] (%/ °C)	-1.9 0.1	-0.9	-0.2	-2.5	?	0.2	0.1

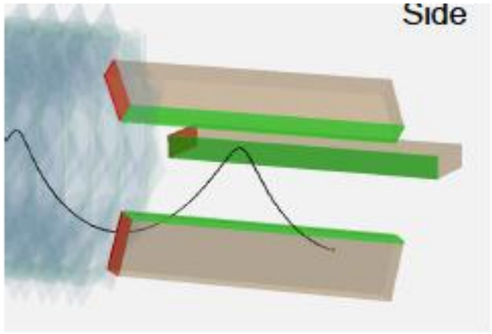
Calorimeter vane design is inherited from MECO

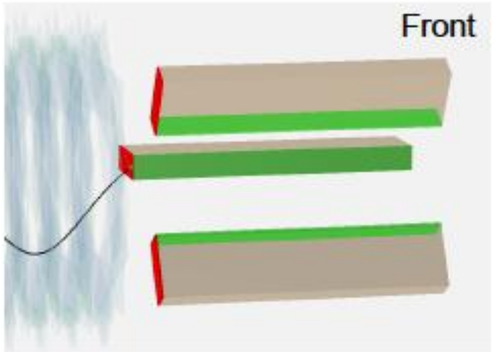
A good match to the MECO L-tracker. Not a design that complements the Mu2e T-tracker

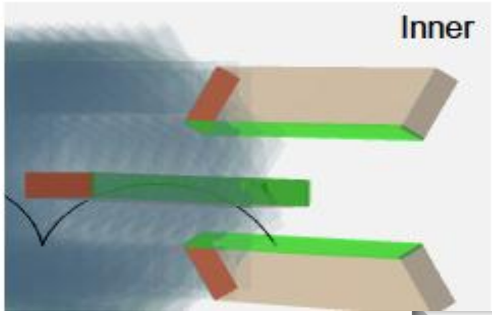
3 kind of hits:
- **Side (good hit)**
- Front (bad hit)
- Inner (bad hit)





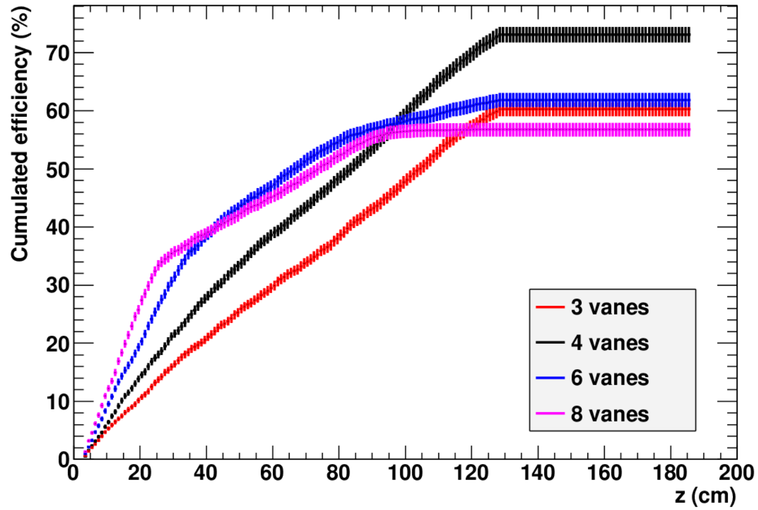




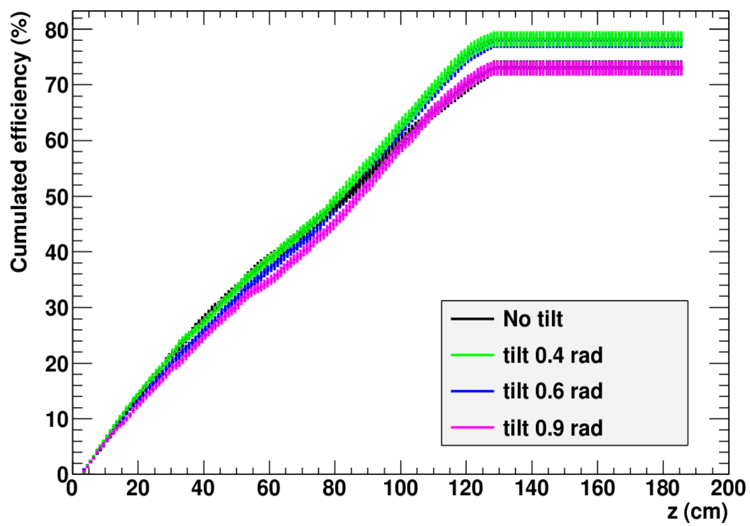


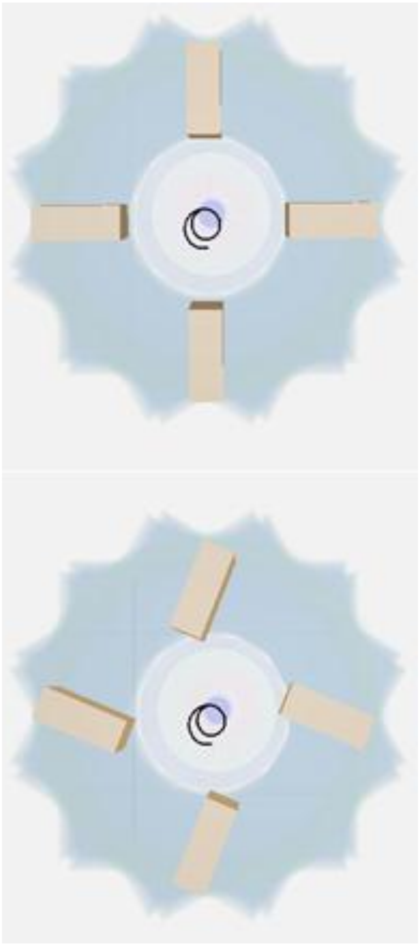
Optimizing the vane geometry

Number of vanes and vane length



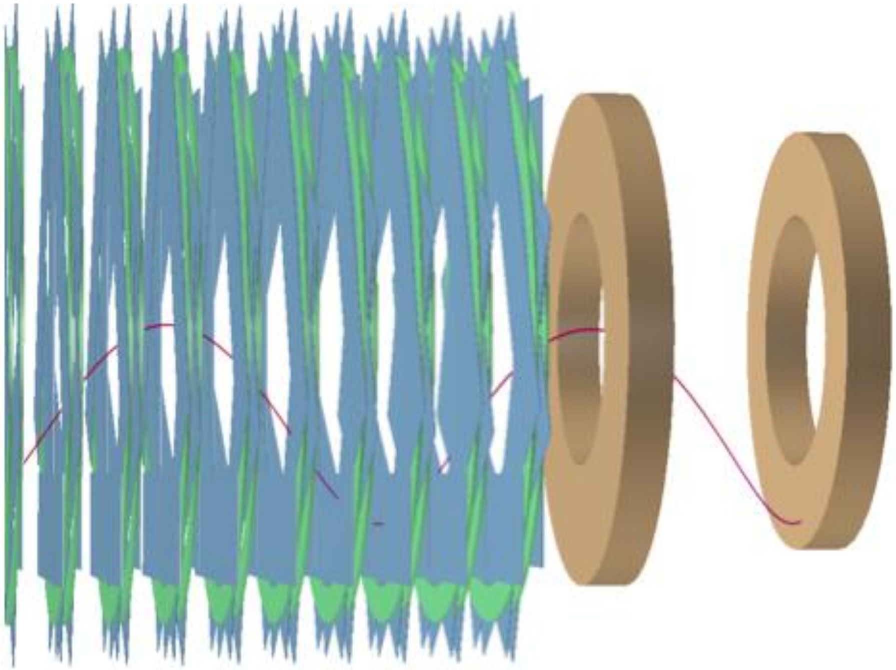
Tilting the vanes improves geometric efficiency

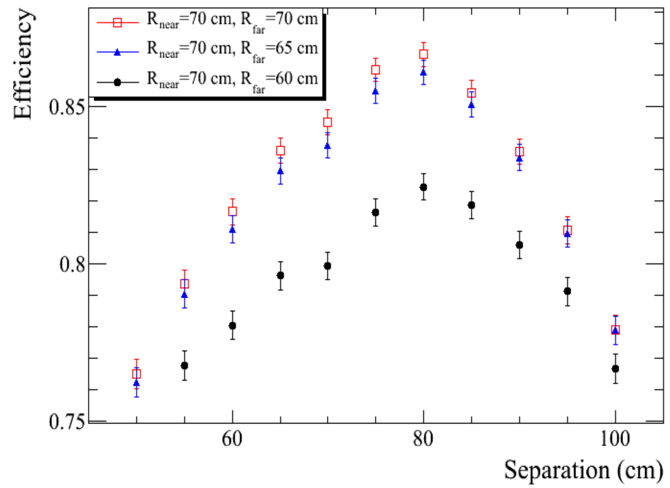


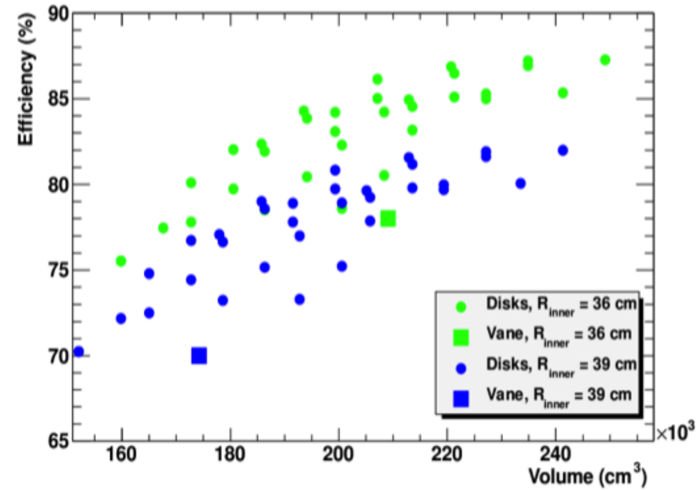


B. Echenard

Disk Geometry



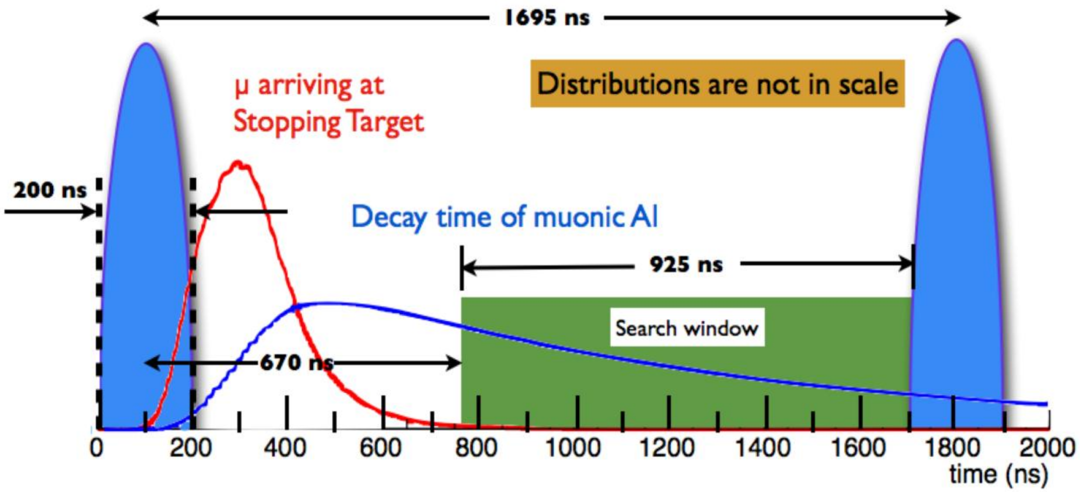




- ❑ Alternate geometry: two discs separated by ½ wavelength of the helical trajectory of the conversion electron
- ❑ Provides greater efficiency for a given crystal volume and substantially higher efficiency (84% of good tracks in the fiducial volume) than the vane geometry
- ❑ The disks face the target ⇒ photon and neutron background from muon capture is seen head on.

C.-h. Cheng, B. Echenard

Time structure of the Mu2e beam



Muon nuclear capture and Decay in Orbit (DIO)

Muon capture on Al has two dominant final states:

- nuclear capture, ~ 60% $\Rightarrow n, p, \gamma$
- muon DIO, ~ 40% $\Rightarrow$ high energy tail is an irreducible background to μ to e conversion. Suppressed by excellent momentum resolution

Required extinction < 10^{-10}

Prompt beam-related background

Suppressed by a delayed "live" window which starts about 670 ns after the beam pulse.

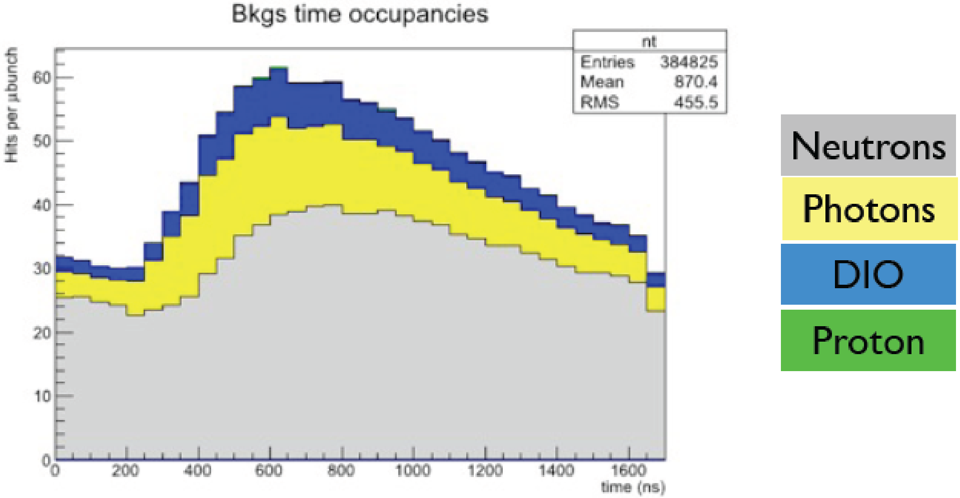
Radiative Pion Capture

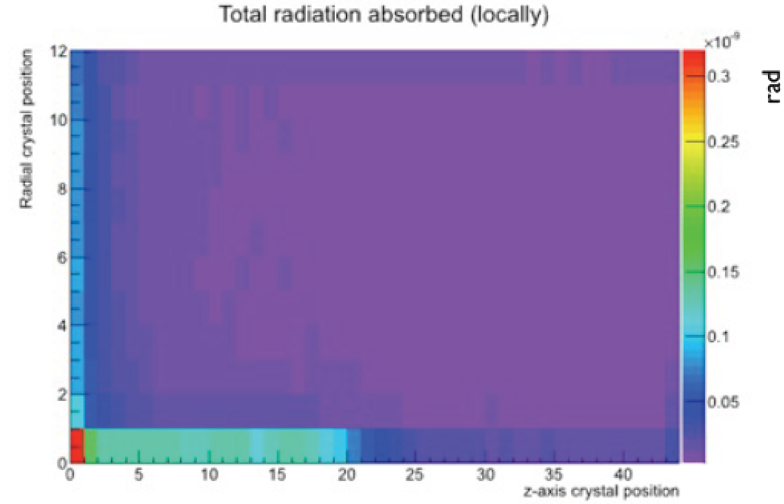
Negative pions stopped in the Al target:

$$\pi^- N \rightarrow \gamma N^{Z-1}, \gamma \rightarrow e^+e^-$$

About 2 x 10^{-4} decay electrons are in the momentum signal region for 3.6 x 10^{20} pot

Calorimeter hit rates – DIO + μ capture

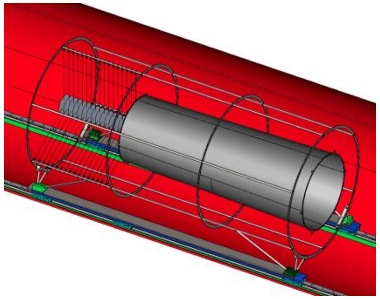


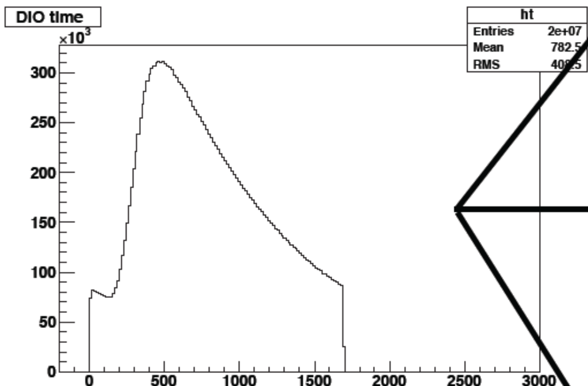


Background	n Hit (0 - 600 ns)	n Hit (600 - 1694)	Hits per µbunch	Rates (MHz) (0 - 600 ns)	Rates (MHz) (600 - 1694)	Rates (MHz) per µbunch	Rate single crystal per µbunch (average)	Absorbed rad µbunch	Absorbed rad µbunch single cry (av.)
DIO	50	99	149	83	90	88	0.0416	5.91E-09	2.80E-12
Ejected p	1.5	3.8	5.3	2.5	3.5	3.1	0.0015	1.07E-09	5.07E-13
Ejected n	328	755	1083	547	690	639	0.3027	1.57E-08	7.41E-12
Ejected γ	114	189	303	190	173	179	0.0847	4.29E-09	2.03E-12
Total	493	1047	1540	822	957	909	0.4304	3E-08	1.27E-11

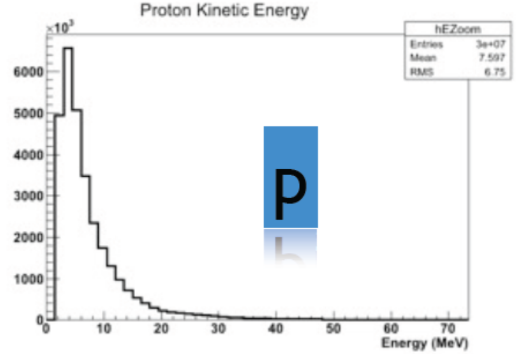
With new normalization, rates reduced by ~0.44)

Background from μ capture on Al target foils

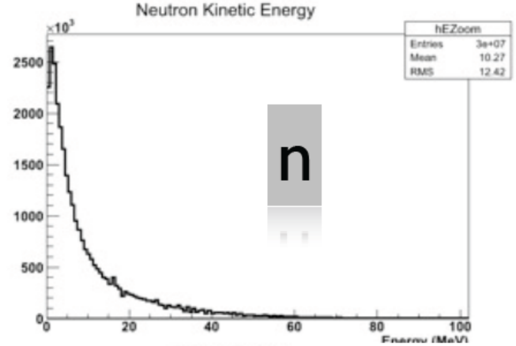




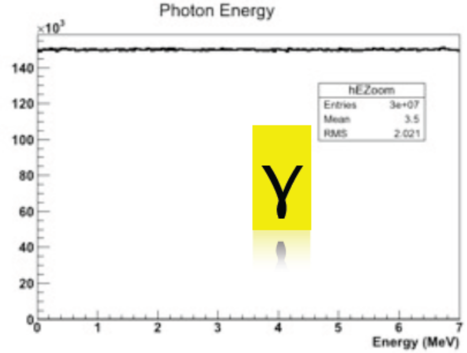
Time generation given by proton spill + muon arrival time (simulation) + negative exponential



- Spectrum from JEPT 33(1971)11 and PRL 20(1967)569
- 0.1 expected per nuclear capture.
- 5,630 per µbunch



- Spectrum from MARS simulation
- 1.5 expected per nuclear capture.
- 84,434 per µbunch



- Spectrum flat from 0 to 7 MeV (first approx.)
- 2 expected per nuclear capture.
- 112,580 per µbunch

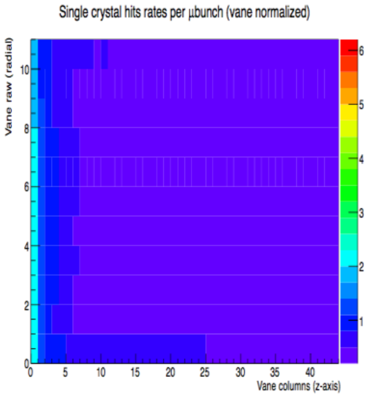
Calorimeter hit rates

- Crystal hits in a microbunch

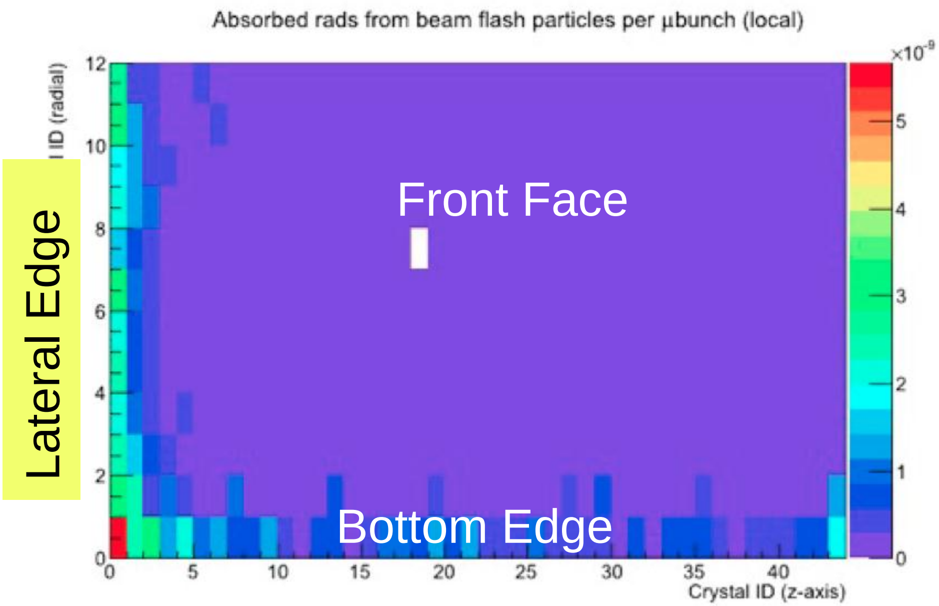
	Total crystal hits (Rate in MHz)	Hits from generated n	Hits from tracks born outside the vanes (sec neutrons + γ)	Hits from tracks born in other vanes (electrons + γ)	Hits from showers only (electrons + γ + HI)	Hottest crystal rate (MHz)
B050	768 (454)	0.5	245	9	512	2.2 (Raw 5 Col 1)

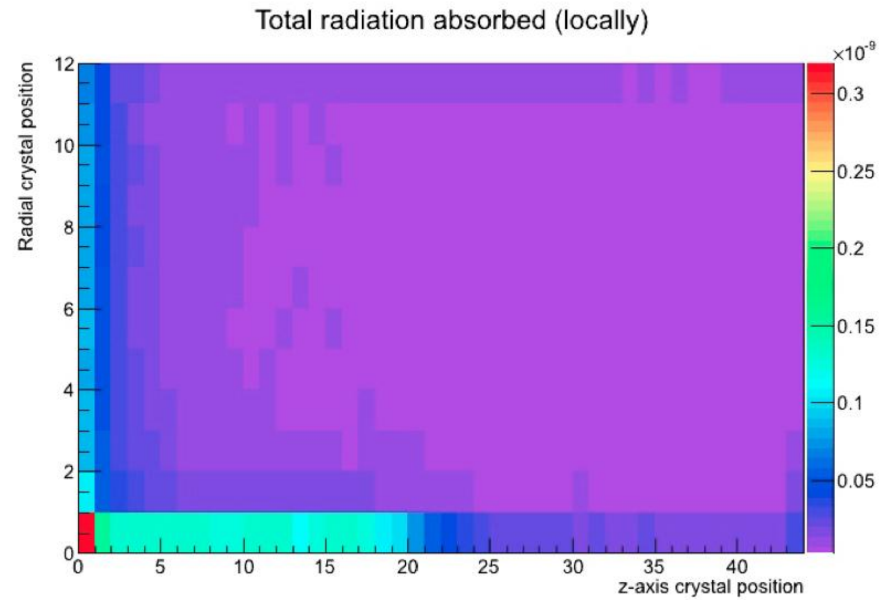
- Crystal hits in live window (t > 700ns)

	Total crystal hits (Rate in MHz)	Hits from generated n	Hits from tracks born outside the vanes (sec neutrons + γ)	Hits from tracks born in other vanes (electrons + γ)	Hits from showers only (electrons + γ + HI)
B050	500 (503)	0	147	6	348



Radiation dose and pattern recognition questions





RADIATION DOSE

Lateral Edge = 300+60 = 360 GY
Front Face = 110 GY
Bottom Edge = 220 GY in first columns
160 GY in second

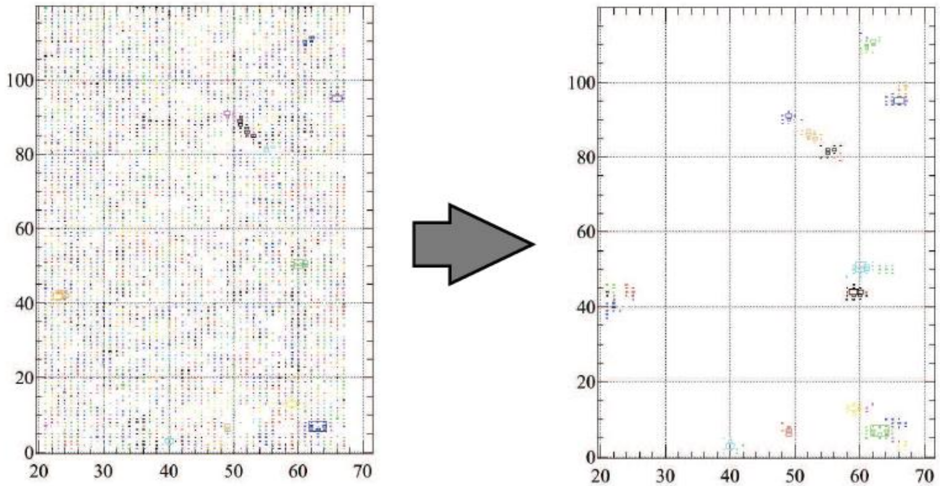
PILEUP in 200 ns window

Neutrons → 0.4 hit/Crystal <E> ~ 0.5 MeV, rms 0.9 MeV
Photons → 0.2 hit/Crystal <E>~ 0.7 MeV, rms ~1.2 MeV

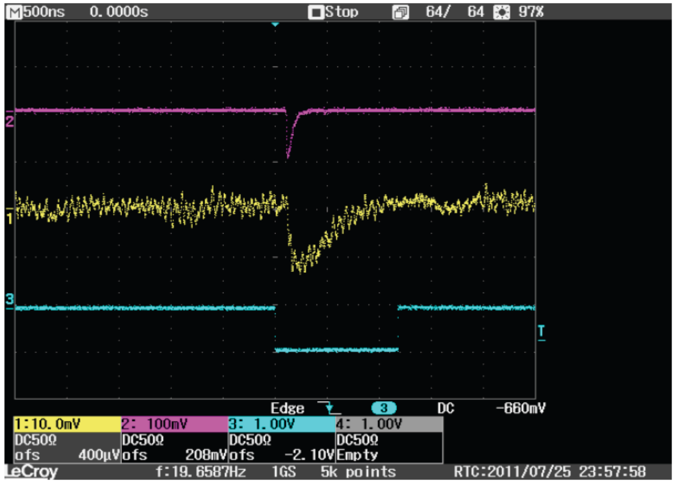
Effect of backgrounds

- Pattern recognition
  - straightforward

A “metaphorical” example from Super*B*

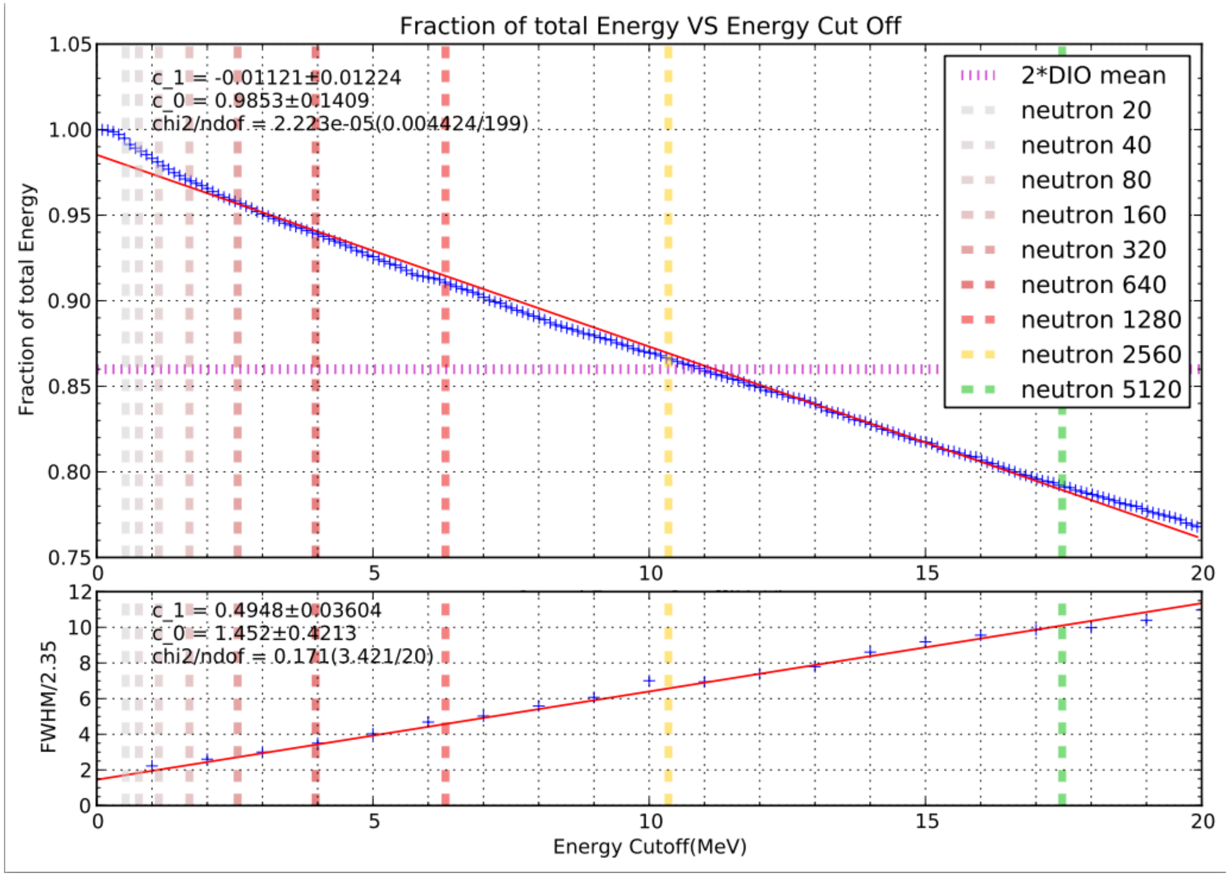


- Pileup – effect on energy resolution



Effect of background on conversion electron resolution

- “Salt and pepper” background included in energy clusters
  - Deteriorates energy resolution



Example Power Staging Plan for the Research Program

Program:	Onset of NOvA operations in 2013	Stage-1: 1 GeV CW Linac driving Booster & Muon, n/edm programs	Stage-2: Upgrade to 3 GeV CW Linac	Stage-3: Project X RDR	Stage-4: Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2450 kW	2450-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-42 kW* + 0-90 kW**	0-84 kW*	0-172 kW*	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	0-172 kW*	1000 kW
1-3 GeV Muon program, e.g. Mu2e-2	~8 kW	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1870 kW	1870 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-1000 kW	0-1000 kW
# Programs:	4	8	8	8	8
Total max power:	735 kW	2222 kW	4284 kW	6492 kW	11870kW

Project X Advantages for Mu2e (from Bob Bernstein's talk)

- *Beam Power*:
  - Aside from raw statistics, lets us solve other problems
- *Time Structure*
  - A problem in Mu2e/Booster Era is radiative pion capture
  - Too detailed for this talk, but "wait" for pions to decay
  - Beam at Mu2e is 200 ns wide and that yields background, since you can't wait forever!
  - PX can give $\mathcal{O}$(10 nsec) beam widths, a huge improvement!
- *Lower Energy*
  - Another problem in Mu2e/Booster is antiproton production
    - Antiprotons wander down beamline (same charge as μ^-), annhihilate, and make pions -> radiative pion capture
    - We're on a threshold for pbars, so slightly lower energy yields huge reduction
- *Can tradeoff the above to optimize sensitivity*

Extrapolating Mu2e to Project X (calorimeter view)

- Assume Project X linac at 4MW
- Specialized to Mu2e:
  - Low beam energy ($\rightarrow$1 GeV) to remove $\bar{p}$ contamination
  - Shorter spill (*e.g*. 200ns$\rightarrow$100ns)
  - Similar sensitive time window (*e.g.* 1μs)
  - Thus 10% duty cycle $\Rightarrow$ 400kW (currently 8kW)
    - Rate increase in sensitive window = x50 !
- How to cope?
  - Shorter integration time and/or faster scintillators
  - Improved time resolution
- Explore alternative crystals
  - Ren-yuan Zhu has an extensive compilation of candidates
    - See his talk this afternoon

Can a calorimeter function at Project X?

The purpose of the calorimeter is to confirm that a reconstructed track of a $\mu \to e$ conversion electron candidate is well-measured, and was not created by a spurious combination of hits in the tracker.

1. Measure the position of the conversion electron $\to \sigma(x) \le \mathcal{O}(1\ \text{cm})$. *crystal size* r_M
2. Compare the energy deposited in the calorimeter to the reconstructed track momentum $\to \sigma(E) \le \mathcal{O}$ (2%), with an uncertainty in the energy scale small compared to the resolution. τ_{scint}, t_{int}
3. Compare the time of the energy deposit in the calorimeter to the time determined from the tracker $\to \sigma(t)$ $\mathcal{O}$ (≤1 ns). t_r
4. Provide particle identification to separate, for example, electrons from muons. t_r
5. Provide a trigger that can be used for event selection t_r
6. Maintain functionality in a ~~50~~ 500-5000 Gy/year radiation environment with light yield loss < 10% *rad hardness*

Rad hard scintillating crystals with faster decay time

Crystal	BaF_2	BGO	LYSO(Ce)	PWO	PbF_2	$LaBr_3$(Ce)	$LaCl_3$(Ce)
Density (g/cm^3)	4.89	7.13	7.40	8.3	7.77	5.29	3.86
Melting Point (°C)	1280	1050	2050	1123	824	788	859
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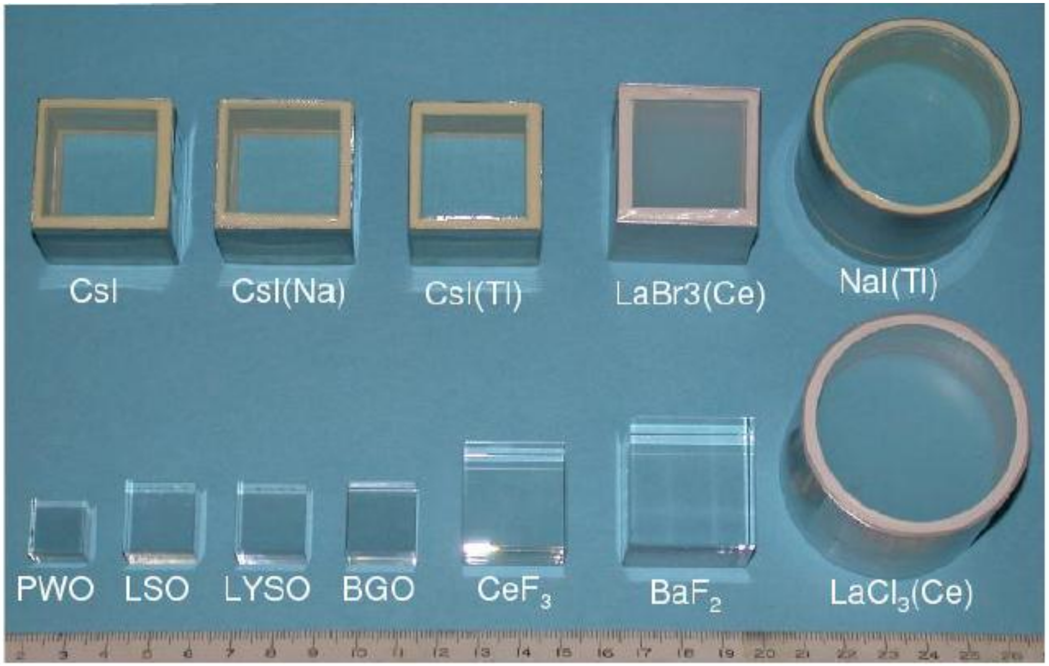
Refractive Index [a]	1.50	2.15	1.82	2.20	1.82	1.9	1.9
Hygroscopicity	No	No	No	No	No	Yes	Yes
Luminescence [b] (nm) (at peak)	300 220	480	402	425 420	?	356	335
Decay Time [b] (ns)	650 0.9	300	40	30 10	?	20	570 24
Light Yield [b,c] (%)	36 4.1	21	85	0.3 0.1	?	130	13 42
d(LY)/dT [b] (%/ °C)	-1.9 0.1	-0.9	-0.2	-2.5	?	0.2	0.1

Are there crystals that can function better at Project X?



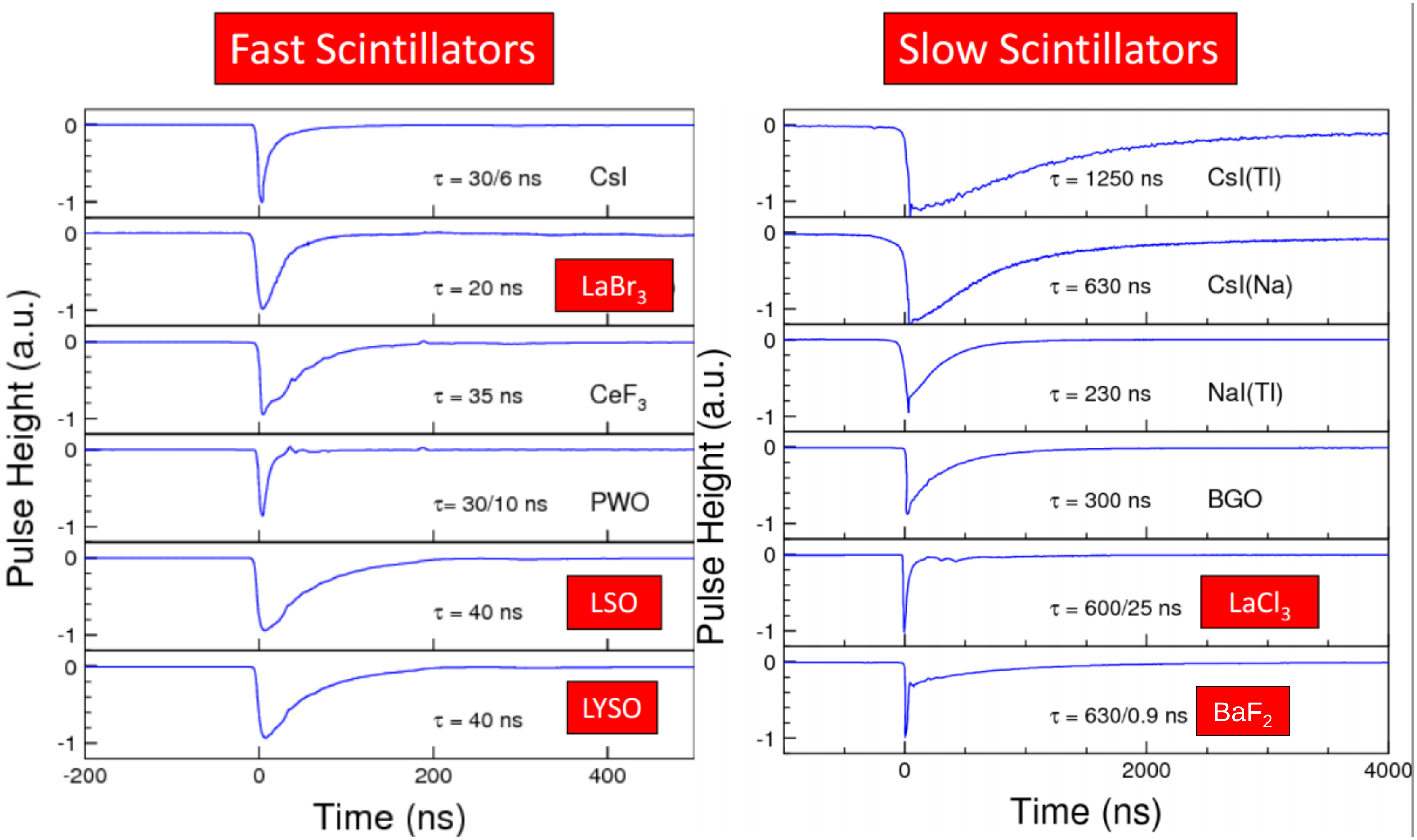
1.5 X_0 Cube Samples:

Hygroscopic: Sealed

Non-hygro: Polished

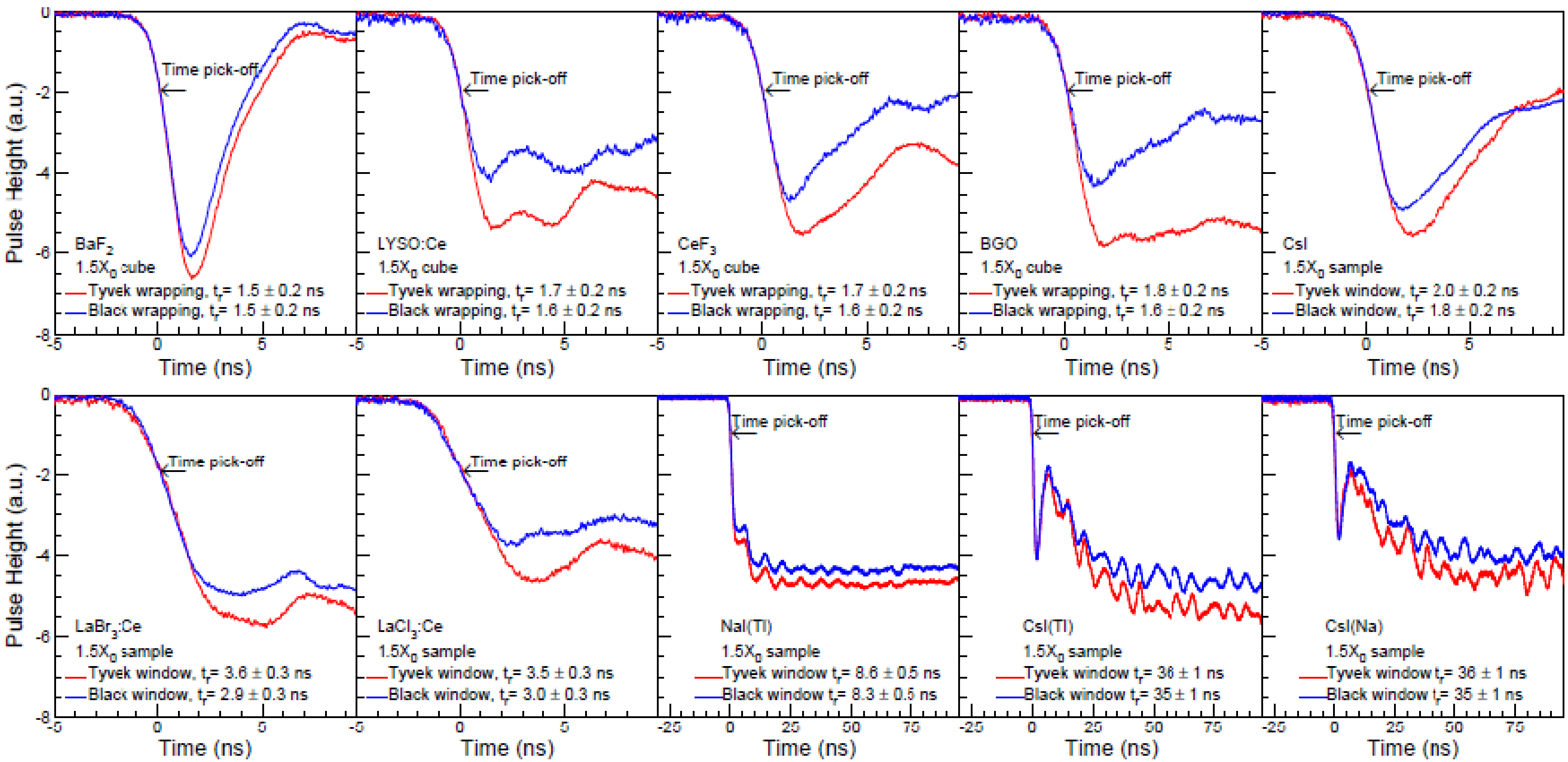
- Crystals with larger Molière radius require more channels to achieve comparable position resolution
- Hygroscopic crystals must be sealed or kept in an inert atmosphere

Scintillation pulse shapes



Pulse shape for 1.5 X_0 samples

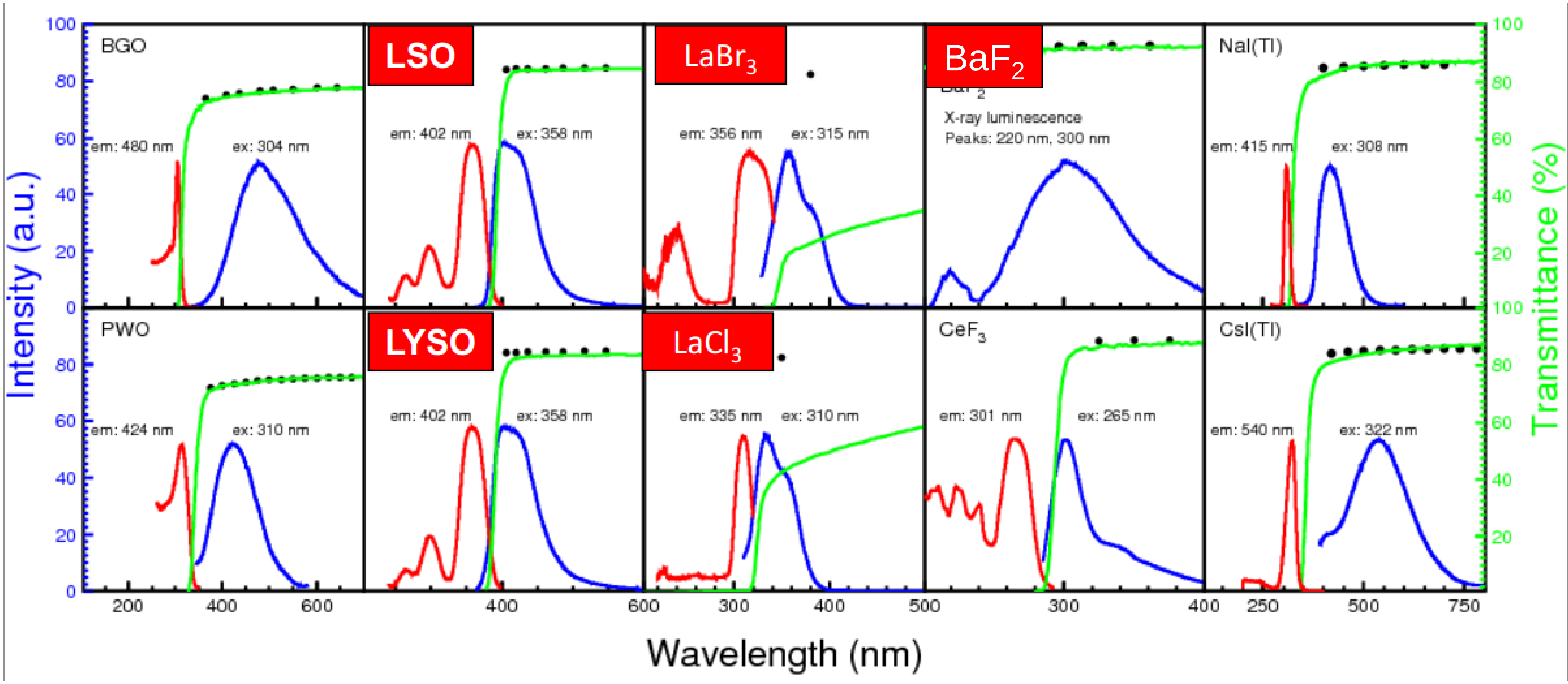
- PMT readout (Hamamatsu R2059)



Rise time dominated by photodetector response and, in large crystals, by light collection time due to path length differences

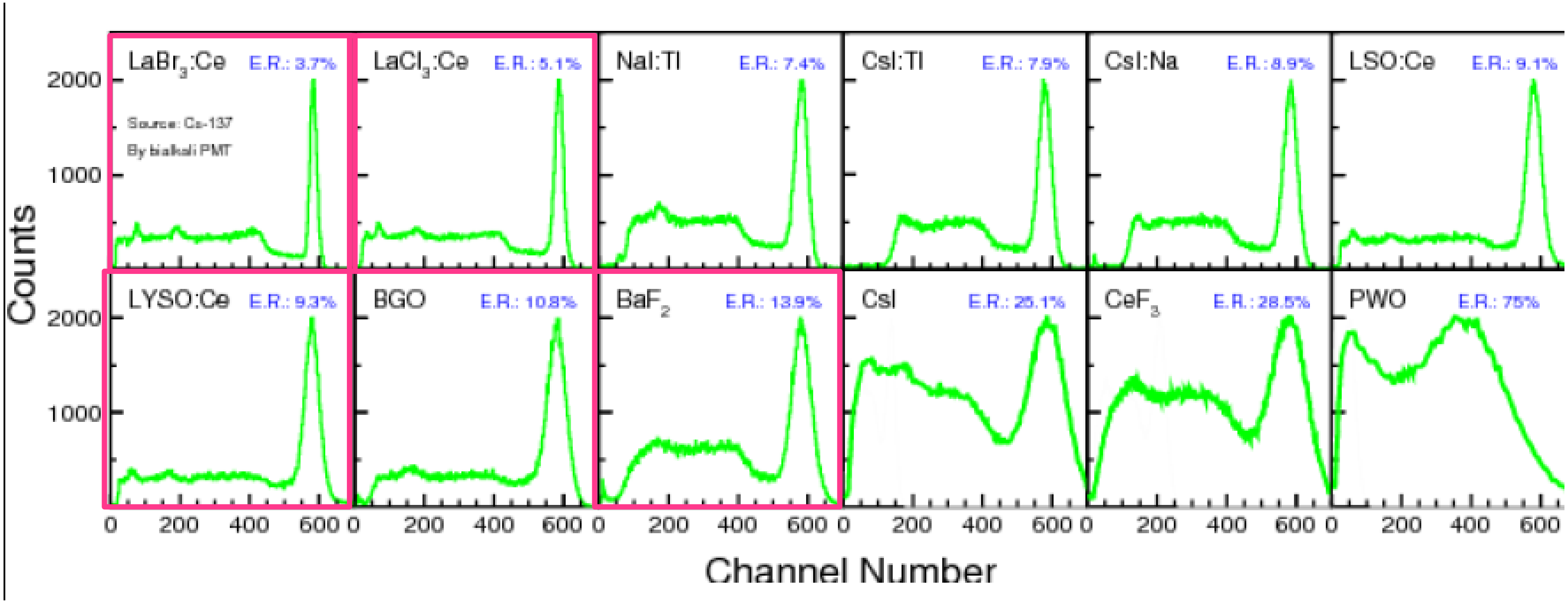
Crystal scintillation spectrum

- Decent match to an APD



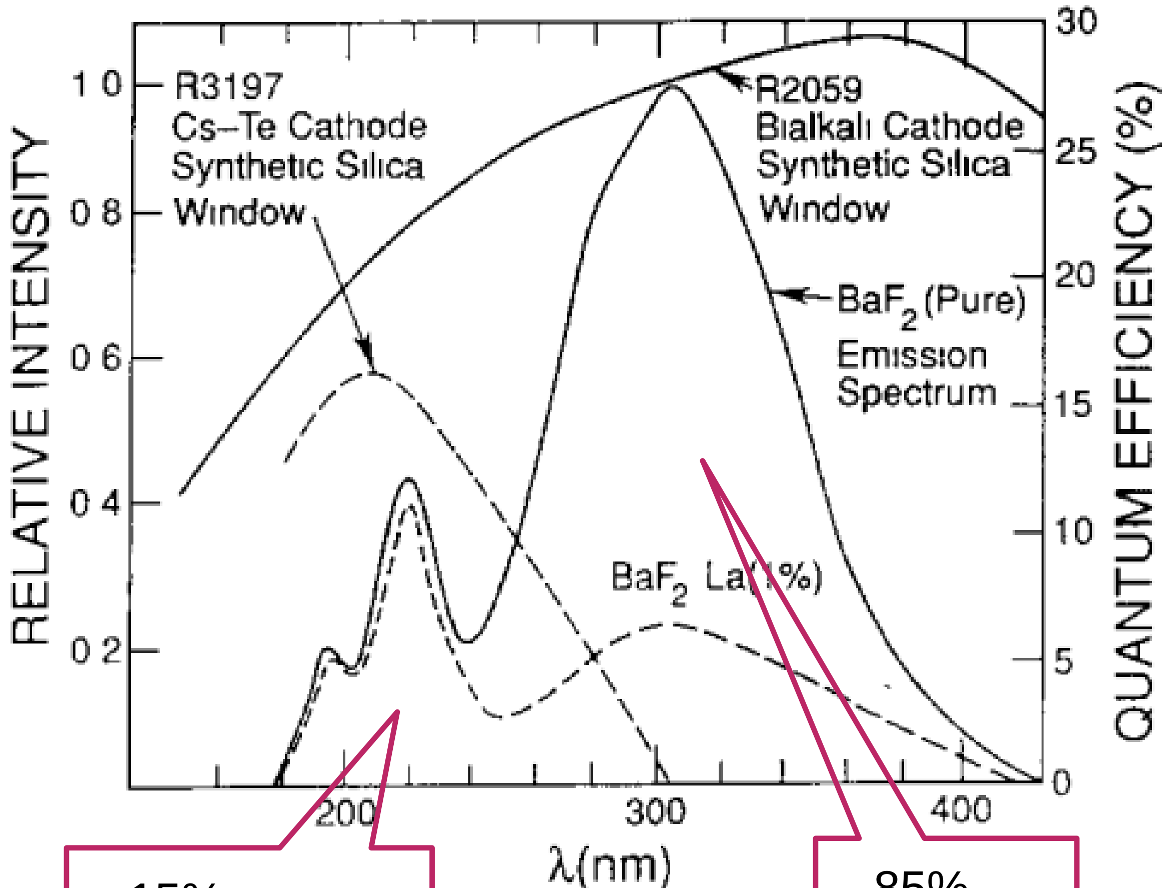
Benchmark: resolution on ^{137}Cs 662 keV line

- $LaBr_3$ (Ce) has best intrinsic resolution – Homeland Security interest



BaF_2 scintillation spectrum

- Total light output = 1.2 x 10^4 photon/MeV



15%
600-800 ps

85%
630 ns

BaF_2 scintillation

- We need a "solar blind" solid state device to read out the BaF_2 fast component and ignore the slow component
- Such devices are being developed
  - APDs with SiC exist
    - Small (100x100µm to 1x1mm)

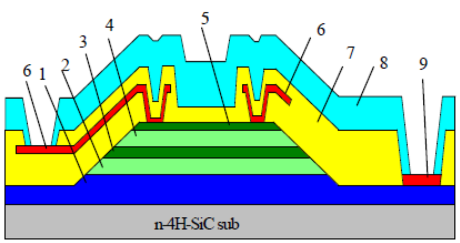
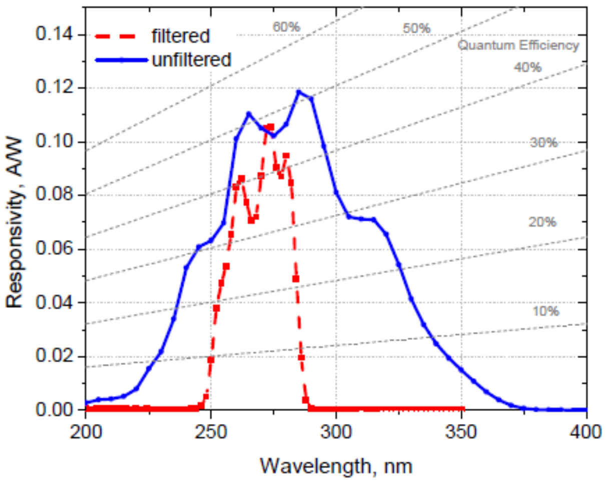


Figure 1. Schematic cross-sectional view of the 4H-SiC SAM-APD , 1 – p-layer, 2 – n- -layer, 3 – n- layer, 4 – n- -layer, 5 – n+-layer, 6 – n-contact, 7 – SiO2 layer, 8 – filter, 9 – p-contact

Alexey Vert, Stanislav Soloviev, Alexander Bolotnikov, and Peter Sandvik
Micro and Nanostructures Technologies
General Electric Global Research Center
Niskayuna, NY, USA



  - Larger sizes are possible

Figure of merit (Zhu)

Crystal Scintillators	Relative LY (%)	A_1 (%)	τ_1 (ns)	A_2 (%)	τ_2 (ns)	Total LO (p.e./MeV, XP2254B)	LO in 1ns (p.e./MeV, XP2254B)	LO in 0.1ns (p.e./MeV, XP2254B)	LY in 0.1ns (photons/MeV)
BaF_2	40.1	91	650	9	0.9	1149	71.0	11.0	136.6
LSO:Ca,Ce	94	100	30			2400	78.7	8.0	110.9
LSO/LYSO:Ce	85	100	40			2180	53.8	5.4	75.3
CeF_3	7.3	100	30			208	6.8	0.7	8.6
BGO	21	100	300			350	1.2	0.1	2.5
PWO	0.377	80	30	20	10	9.2	0.42	0.04	0.4
$LaBr_3$:Ce	130	100	20			3810	185.8	19.0	229.9
$LaCl_3$:Ce	55	24	570	76	24	1570	49.36	5.03	62.5
NaI:Tl	100	100	245			2604	10.6	1.1	14.5
CsI	4.7	77	30	23	6	131	7.9	0.8	10.6
CsI:Tl	165	100	1220			2093	1.7	0.2	4.8
CsI:Na	88	100	690			2274	3.3	0.3	4.5

- Ren-yuan will survey new crystals in much more detail in his presentation this afternoon

An R&D plan

- It may be possible for the Mu2e calorimeter (tracker ???) to cope with initial Project X rates by shortening the signal integration time
  - It is straightforward to study the effect on energy resolution
- At 50x, it is likely that a new approach will be necessary
  - Something completely different
  - A crystal with a shorter scintillation decay time
    - There are candidates: BaF_2, $LABr_3$(Ce), $LaCl_3$(Ce), ……
    - Before these crystals can be employed in an HEP experiment, further R&D will be necessary
      - Crystals
        - » Size
        - » Production efficiency
        - » Impurities – radiation hardness
        - » Uniformity
      - Readout devices
        - » Spectral response
        - » Size
        - » Radiation hardness