Radiation Modeling and Shielding Design for the Mu2e Branching Ratio Normalization Detectors

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Purdue University

For the STM Group of Mu2e Experiment at Fermilab

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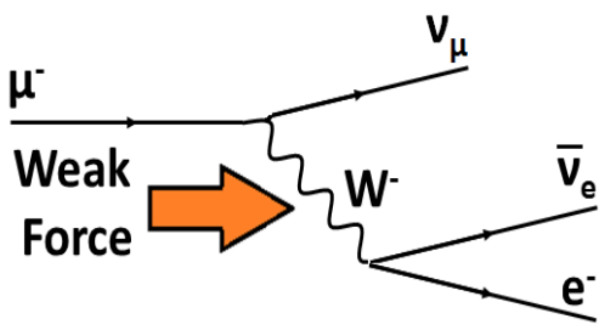
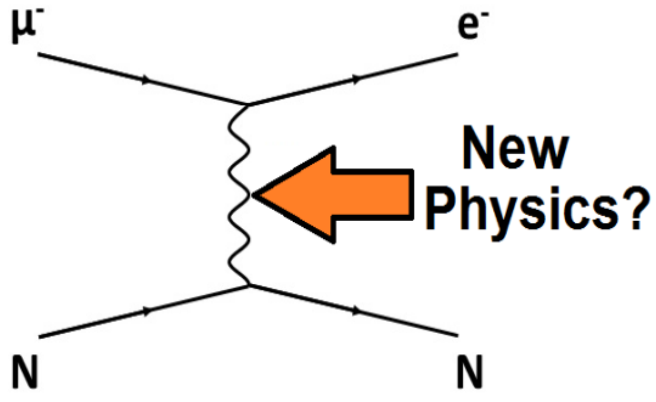
Overview of Mu2e Experiment

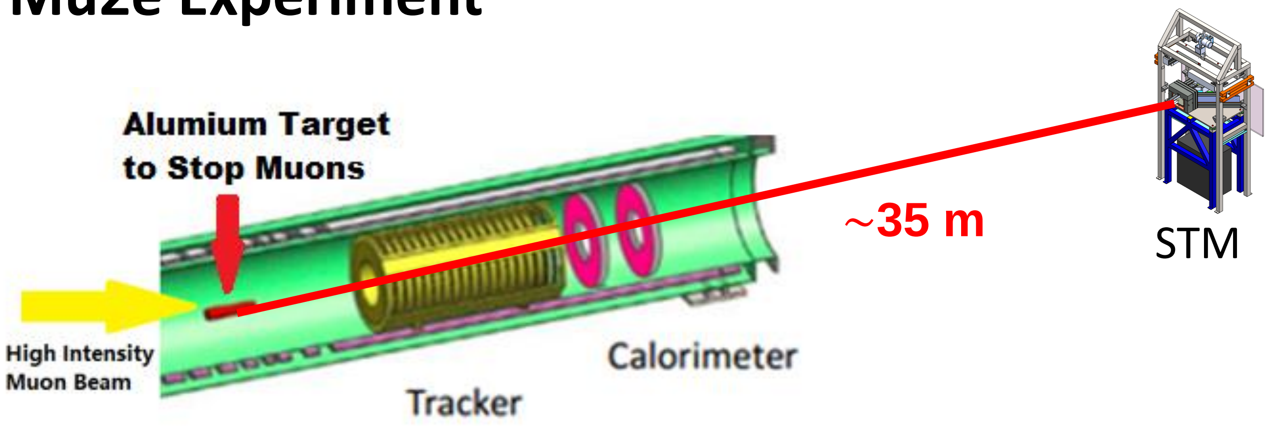
Muon-to-Electron Conversion





$$\mu^- + N \rightarrow e^- + N$$ → **Charged Lepton Flavor Violation (CLFV)**

Mu2e Experiment



Mu2e searches for CLFV by the ratio:

$$R_{\mu e} = \frac{\mu^- + A(Z,N) \rightarrow e^- + A(Z,N) \quad ①}{\mu^- + A(Z,N) \rightarrow \nu_\mu + A(Z-1,N) \quad ②}$$

① Measured by the tracker and the calorimeter

② Measured by the Stopping Target Monitor(STM)

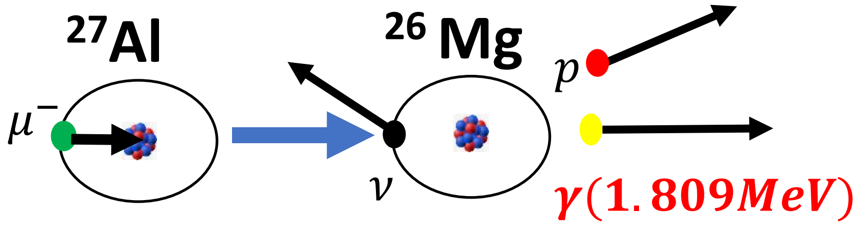
Mu2e goal

- Mu2e Experiment stops $3.7 \times 10^{10}\ \mu^-\ \mathrm{sec}^{-1}$.
- $\sim 10^{18}$ muons over three years.
- Charged Lepton Flavor Violation (CLFV) single-event-sensitivity(SES) of 2.5 x 10^{-17}.
- 10,000 times better than previous limit (SINDRUM II).

Stopping Target Monitor(STM)

STM Mission:

Normalize the mu2e experiment's standard model background with 10% precision.

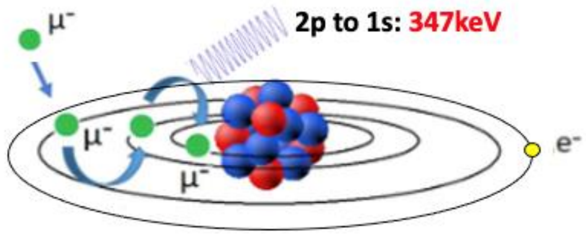


STM Signal:

$$\mu^- + {}^{27}_{13}Al \rightarrow \nu_\mu + {}^{26}_{12}Mg + n + \gamma$$

1.809 MeV γ-ray 51(5)% of μ captures

The main signal in the mu2e normalization.

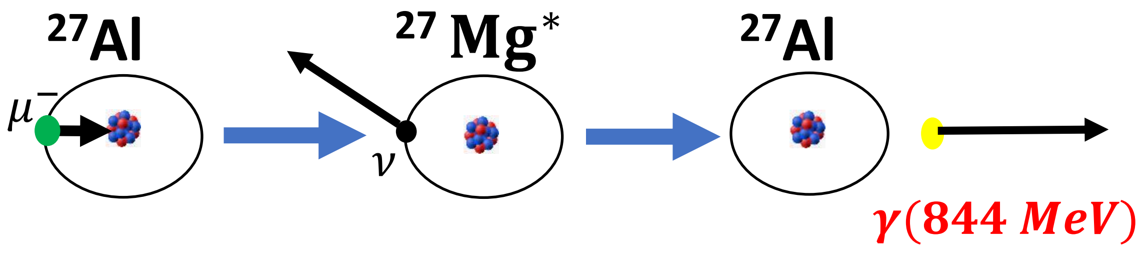


$$\mu^- + {}^{27}_{13}Al \rightarrow \mu^- + {}^{27}_{13}Al + \gamma$$

347 keV X-ray , 2p-1s, 79.8(8)% of μ stops

$$\mu^- + {}^{27}_{13}Al \rightarrow \nu_\mu + {}^{27}_{12}Mg$$

$${}^{27}_{12}Mg \rightarrow {}^{27}_{13}Al + \gamma$$



844 keV γ-ray (10%-13%)×71.8% ≈9.3% of μ captures

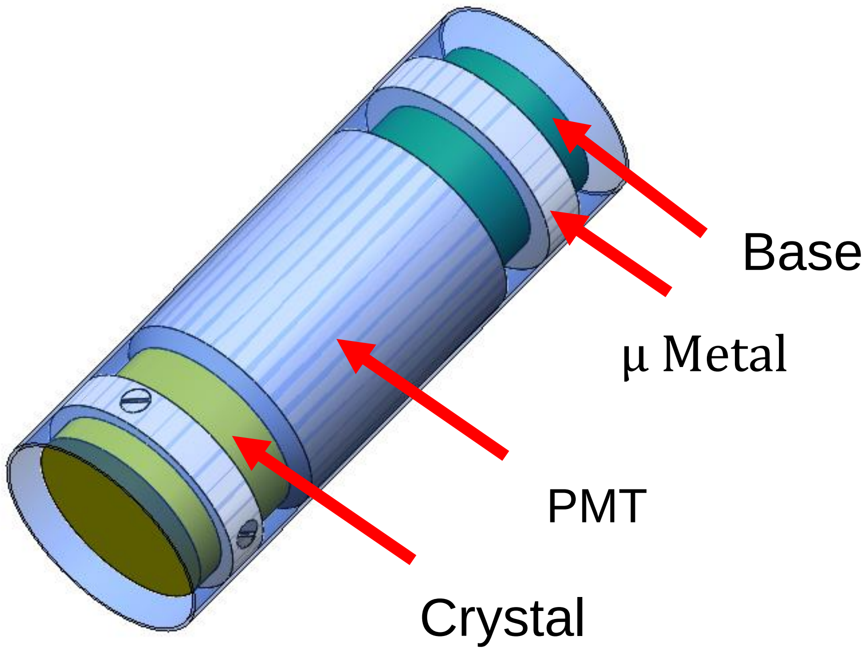
STM Detectors:

$LaBr_3$ Detector

Energy Resolution(@662keV): 7 keV

Rising edge ~5 ns Decay tail: ~ 26 ns

Rate Capability: ~800 kcps with average energy 5 MeV, 4.0 TeV/s

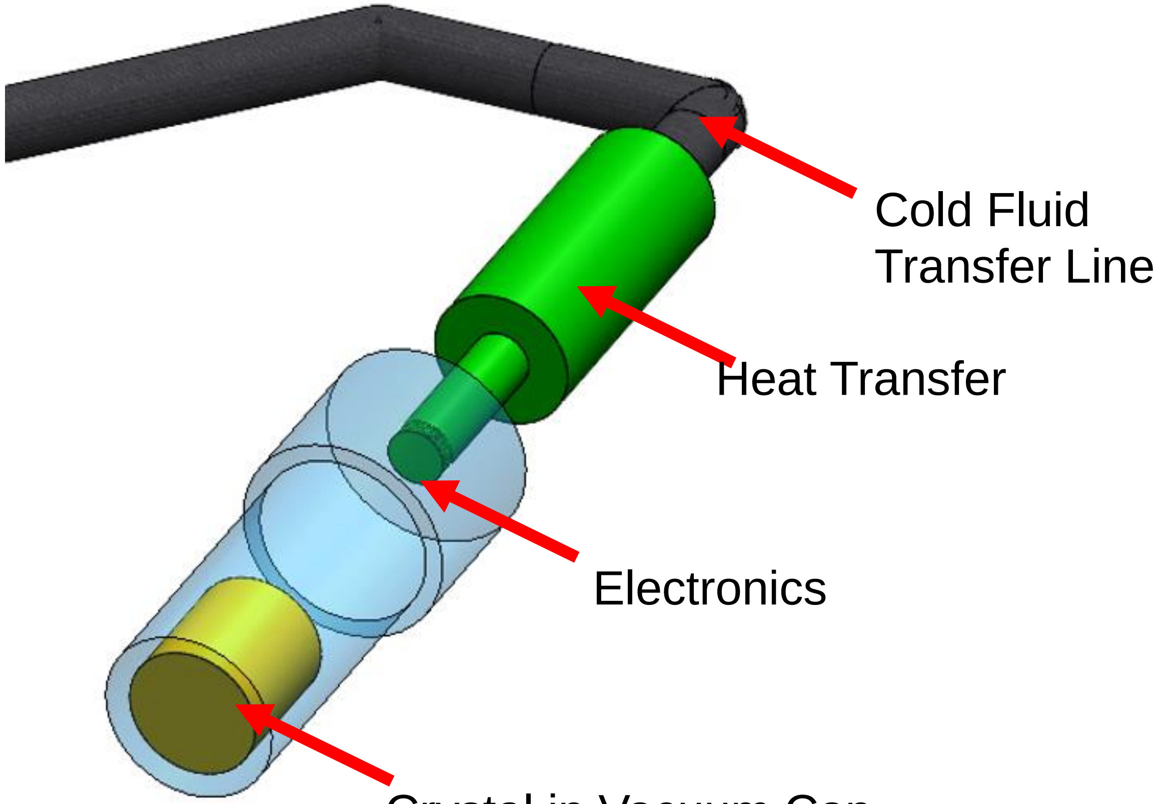


HPGe Detector

Energy Resolution(@662 keV): 0.8 keV

Rising edge: ~400 ns Decay tail: ~60 μs

Rate Capability: ~73 kcps with average energy 5 MeV, 0.37 TeV/s



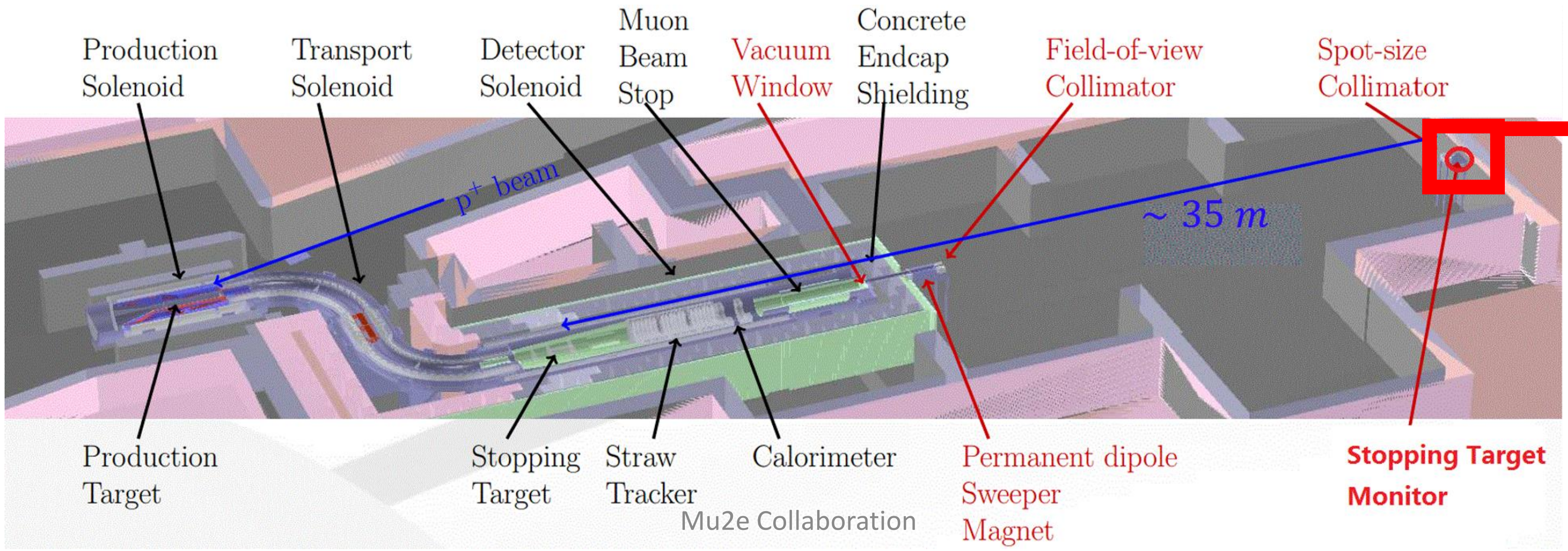
STM Flash Background and Protection Plan

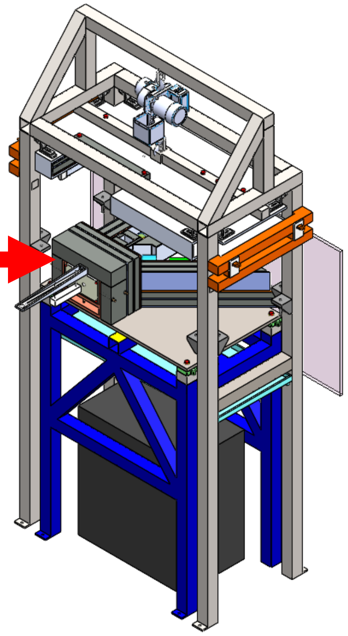
Strong Radiation Flash:

- Stopping Target generates energy flux 3.2×10^8 TeV sec^{-1}, consisting of muons, electrons, neutrons, X-rays and γ rays.
- High energy flux overwhelms electronic rate capability.
- Flux cause radiation damage to detectors.

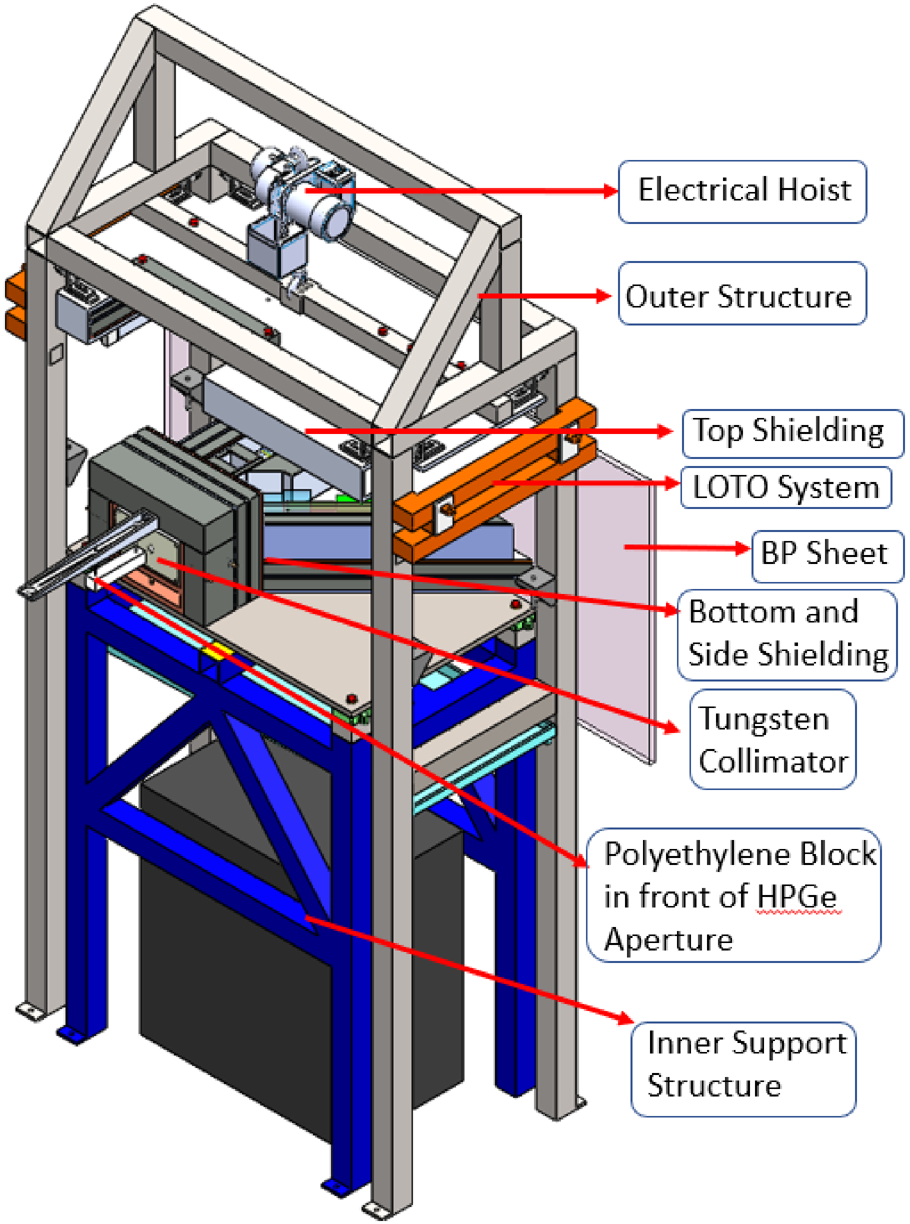
Protection Plan:

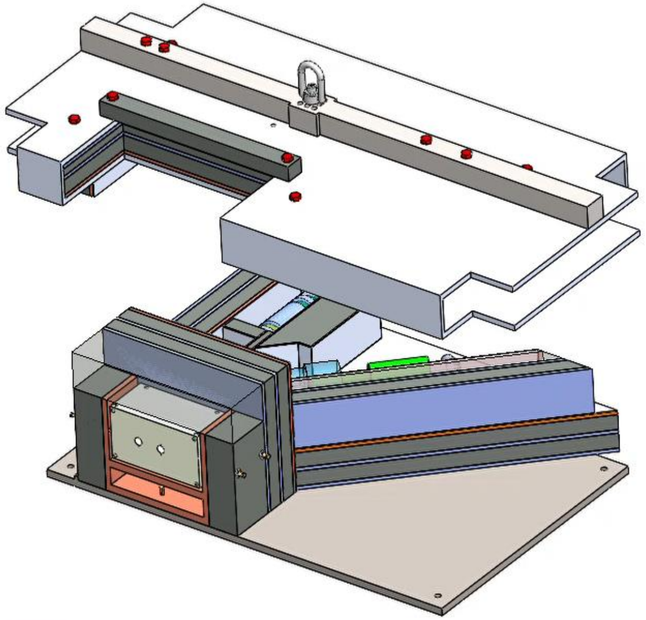
- Stopping Target Monitor(STM) is placed ~35 m away from the Stopping Target.
- A shielding house with small collimator apertures.
- Polyethylene absorbers are placed inside of the Detector Solenoid and inside of the Field-of-View Collimator.
- A permanent Sweeper Magnet may be used to deflect electrons.
- A 390-mm Polyethylene absorber is placed in front of the HPGe detector.





STM Shielding Supporting System

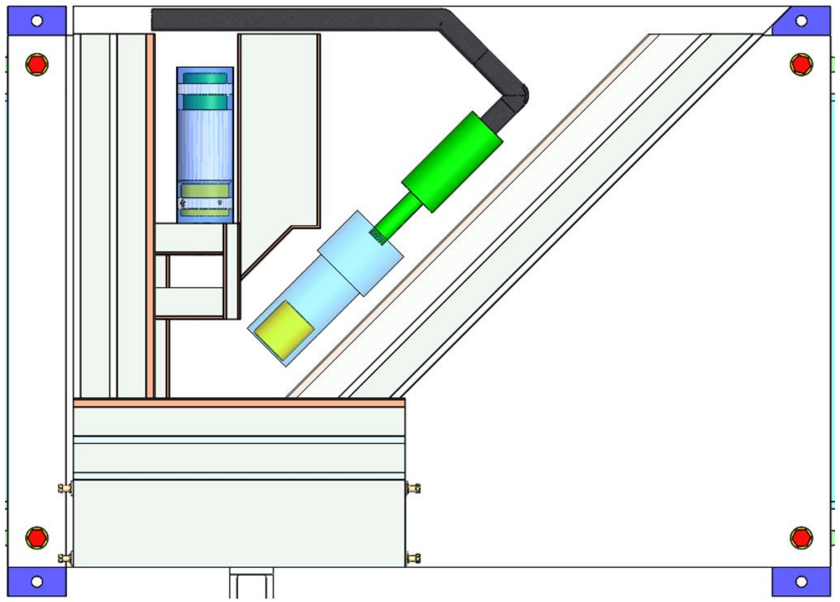


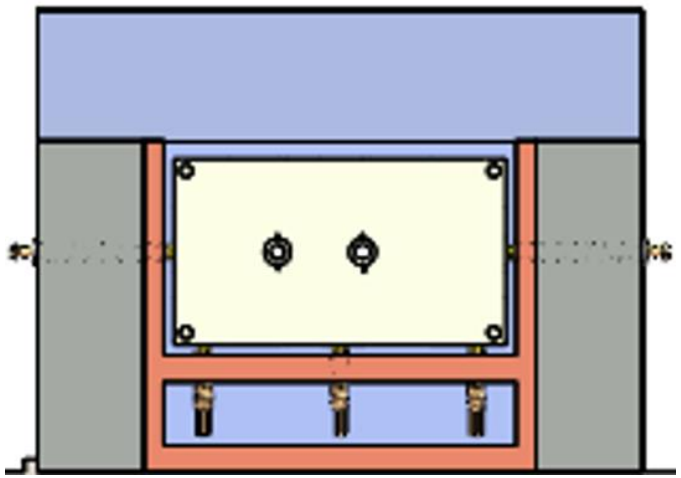


The weight of the shielding house is ~ 6000 lbs.

The house is lifted 91'' above the floor.

The 400 lbs tungsten collimator has a moving range $\pm 1\ cm$ in x and y direction. It needs to be located with precision 25 μm.

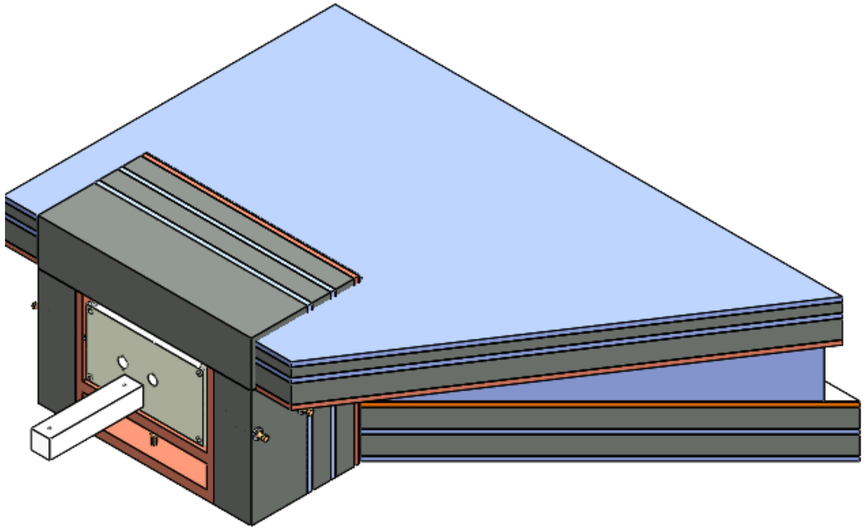




STM Shielding Design

Shielding on each side is a combination of

- Borated Poly – 0.5”
- Lead – 2”
- Borated Poly – 0.5”
- Lead – 2”
- Copper – 0.5”
- Aluminum – 0.1”



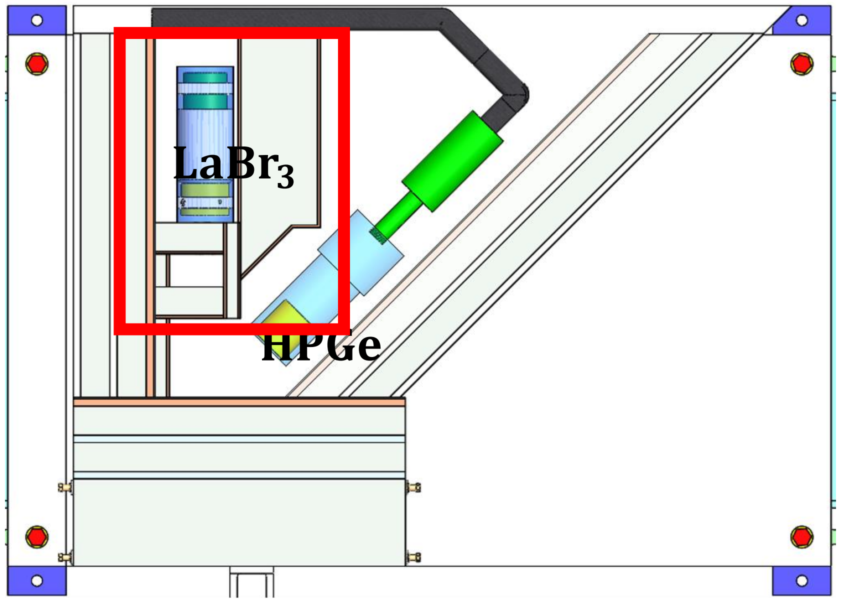
Shielding on the front side is a combination of

- Tungsten – 6’’
- Borated Poly – 0.5”
- Lead – 2”
- Borated Poly – 0.5”
- Lead – 2”
- Copper – 0.5”
- Aluminum – 0.1”

The size of the collimator apertures for the two detectors are both 0.5 cm^2.

There is a 390 mm Polyethylene absorber in front of the HPGe aperture to reduce beam flux.

Internal Shielding



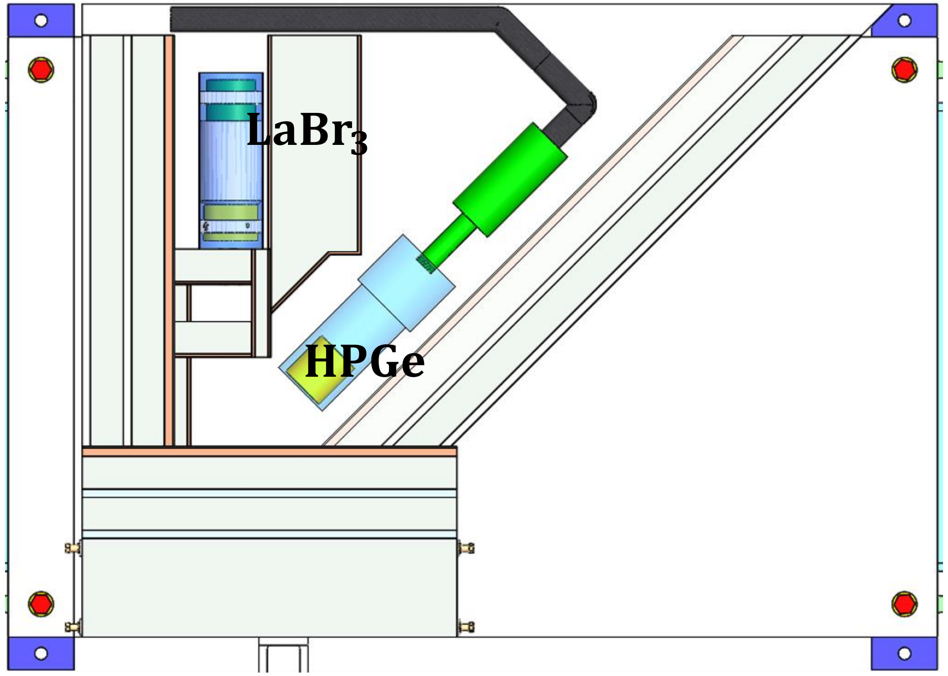
The internal shielding reduces the crosstalk by a factor of ~ 100.

The internal shielding also reduces the radiation background entering the house through shielding walls and mainly through the sides of the collimator.

	LaBr to HPGe		HPGe to LaBr	
	Average Energy (MeV)	Frequency (cps)	Average Energy (MeV)	Frequency (cps)
Internal Shielding	0.12	1.4	1.7	7.0
No Internal Shielding	0.18	388.4	1.90	361.7

STM Radiation Flash Reduction with Protection

	Energy Flux $\text{TeV sec}^{-1}\text{cm}^{-2}$	Reduction Factor
Stopping Target	3.2×10^{8} (TeV sec^{-1})	-
Geometry Factor (35 m)	65	2×10^{-7}
Absorber and Magnet	47	0.72



	Energy Flux $LaBr_3$ detector $\text{TeV sec}^{-1}\text{cm}^{-2}$	Reduction Factor	Energy Flux HPGe detector $\text{TeV sec}^{-1}\text{cm}^{-2}$	Reduction Factor
Shielding House	2.5×10^{-3}	5.3×10^{-5}	1.6×10^{-2}	3.5×10^{-4}
Total Reduction	-	$\mathbf{7.6\times 10^{-12}}$	-	$\mathbf{5.0\times 10^{-11}}$

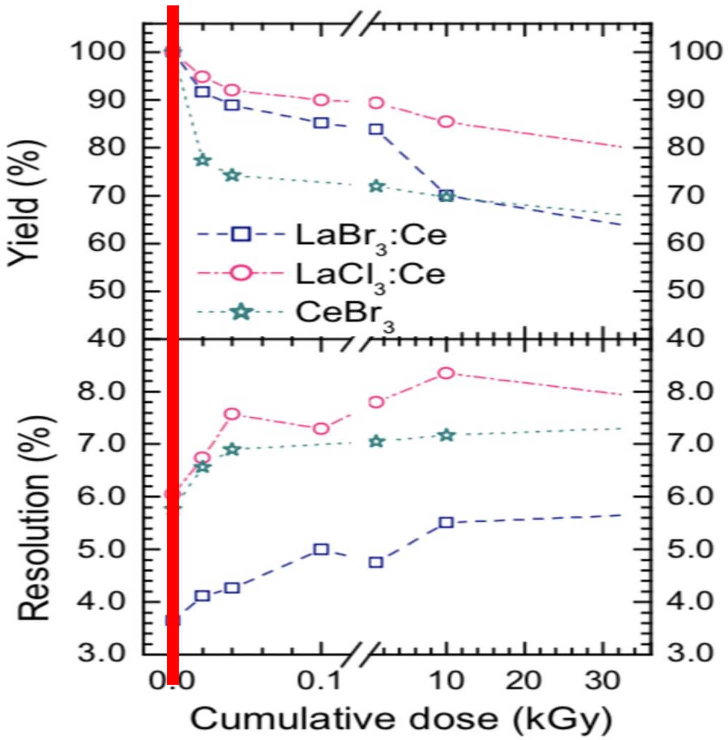
STM Detectors Total Rate Estimation

Total Rate means the radiation entering the shielding house through the collimator apertures and through the shielding wall.

	Rate(Mcps) Nominal/Max	Energy Flux(TeV/s) Nominal/Max	Nominal Background Energy Flux/ Nominal Aperture Energy Flux
$\mathbf{LaBr_3}$ Detector	0.15/0.87	0.55/3.3	$\mathbf{4.77 \times 10^{-3}}$
$\mathbf{HPGe}$ Detector	0.026/0.16	0.12/0.70	$\mathbf{3.16 \times 10^{-2}}$

Radiation Damage Estimation - $LaBr_3$ Detector

Gamma Radiation (Ionization Damage)



For the STM $LaBr_3$ detector at nominal rate 145 kcps and average energy ~3.8 MeV, running 2 years, the cumulative dose is ~0.74 Gy (red line in figure). [1]

The radiation damage to the crystal is negligible.

Neutron Radiation (Displacement Damage)

No damage observed for neutron fluence up to 4×10^9 n cm^{-2} from Am241-Be neutron source. [2]

Expected neutron fluence less than 200 n $cm^{-2}s^{-1}$.

The radiation damage to the crystal is negligible.

Radiation Damage Estimation - **HPGe** Detector

Gamma Radiation(Ionization Damage)

Brookhaven Experiment[3]:

- High-intensity Co-60 source
- HPGe detector performance remained stable up through a Total Ionizing Dose (TID) of at least 7.5 krad of gamma radiation, which equivalent to a total deposition of $\sim 5 \times 10^{14}$ MeV.

Mu2e STM:

Nominal rate 26 kHz, mean Energy 4.6 MeV, time duty factor 0.246. **HPGe at Mu2e STM can run for > 500 years.**

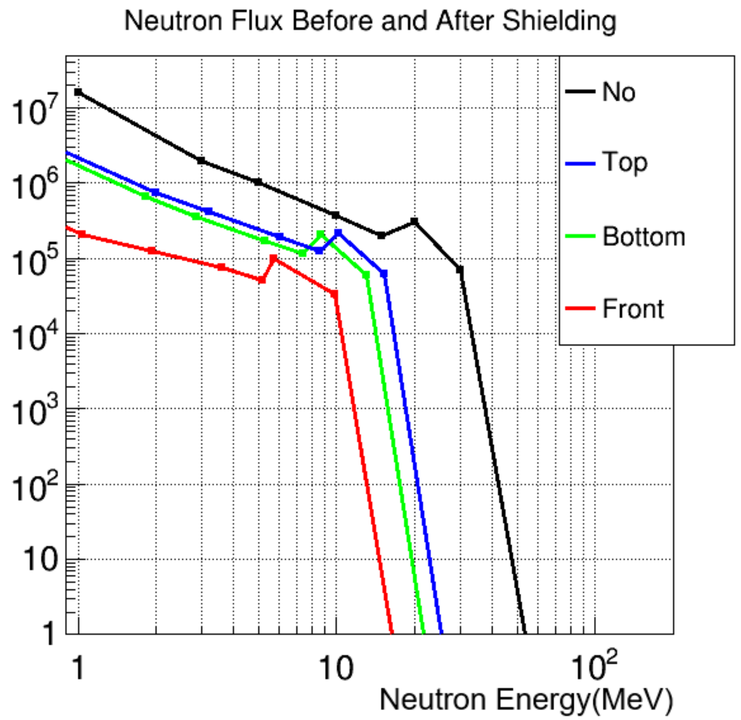
Neutron Radiation(Displacement Damage)

Ortec Experiment[4]:

- Cf_{252} source, high-purity n-type germanium.
- Energy resolution degenerates by a factor of 2 at 10^{10} n cm^{-2}

Mu2e STM:

- The neutron flux is $3.5\times 10^2\ sec^{-1}cm^{-2}$ outside of shielding house.
- STM shielding house reduces neutron flux by a factor of ~ 50.
- **HPGe requires annealing every 12 month.**



Summary

High Energy Flux Protection:

- For LaBr, the ratio between the flux through the shielding and aperture is 4.77×10^{-3}.
- For HPGe, the ratio between the flux through the shielding and aperture is 3.16×10^{-2}.

Detector Radiation Damage Protection:

- The $\mathrm{LaBr_3}$ detector is well protected from radiation damage.
- The running time of the HPGe detector before annealing increases from less than a month to ~ 1 year because of the shielding house.

Companion Talks :
FLF 5I Section, **The Mu2e Experiment: A Search for Charged Lepton Flavor Violation**, Kate Ciampa, 14:30 – 14:45, 07/14/2021
FLF 6I Section, **Normalization of the Mu2e Charged Lepton Flavor Violation Experiment,** Jijun Chen, 16:15 – 16:45, 07/14/2021

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Thanks for your attention!

Q & A

References

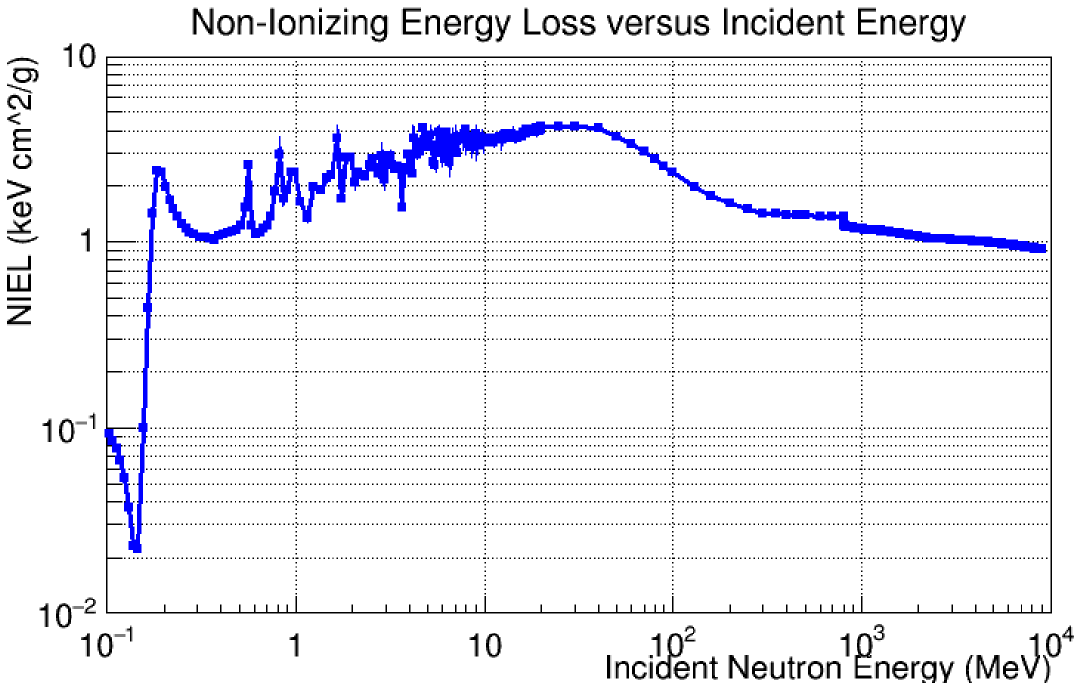
- 【1】W. Drozdowski, P. Dorenbos, A. J. J. Bos, A. Owens and D. Richaud, "Gamma radiation hardness of Ø1” × 1” LaBr3:Ce, LaCl3:Ce, and CeBr3 Scintillators," 2008 IEEE Nuclear Science Symposium Conference Record, 2008, pp. 2856-2858, doi: 10.1109/NSSMIC.2008.4774965
- 【2】Yi L, Zhao-Hui S, Gang L, et al. Study of neutron radiation effect in LaBr3 scintillator[J]. Chinese Physics C, 2015, 39(10): 106003.
- 【3】V. Tishchenko et al., Gamma-ray Irradiation Test of a High Purity Germanium Detector. Mu2e-doc-7042. 26 Apr 2016.
- 【4】Ortec. GMX Series Coaxial HPGe Product Configuration Guide

Neutron Damage to the HPGe

Damage Estimation

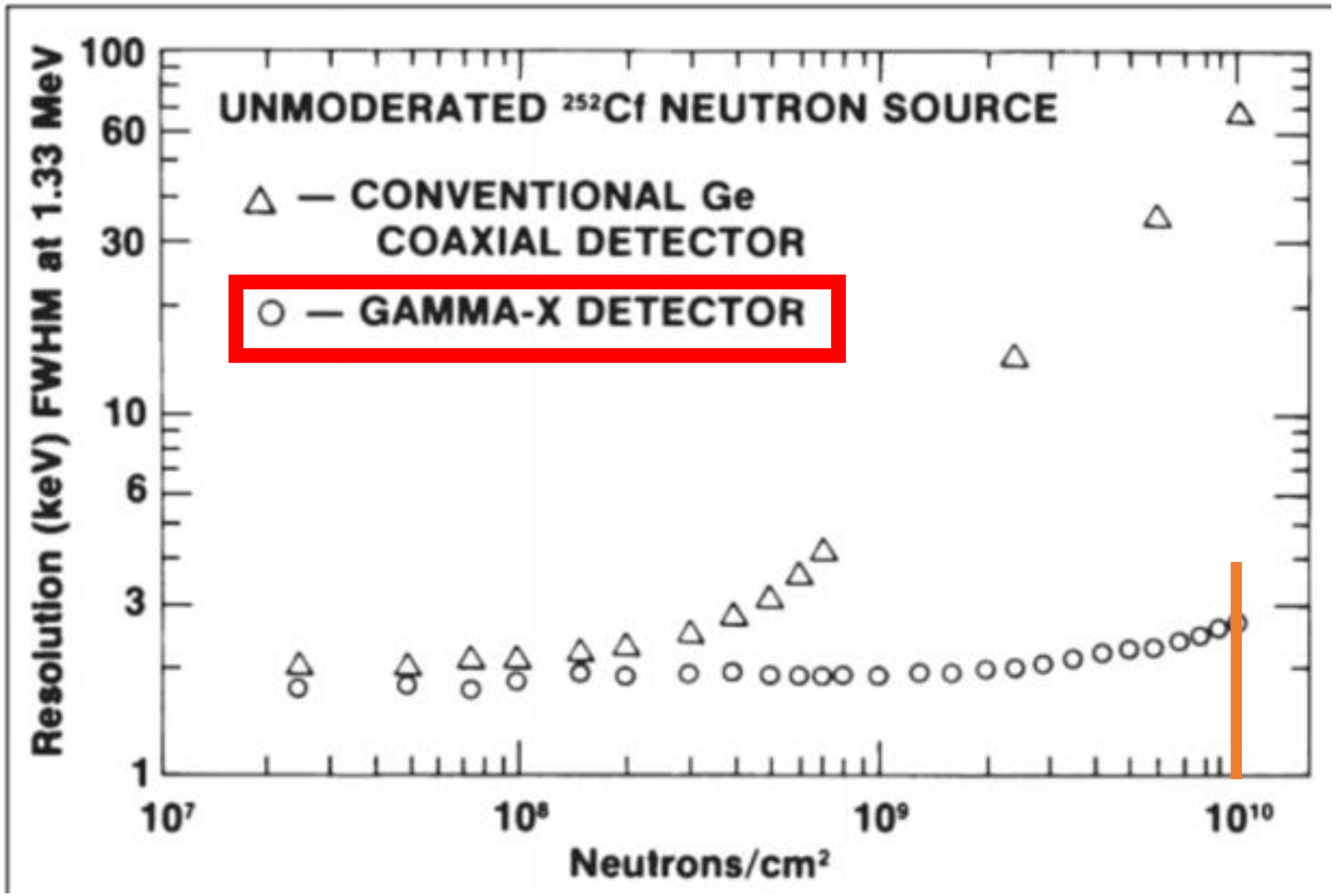
- Neutrons interact with materials primarily by elastic and inelastic collisions or by transmutation, and generally cause displacement damage, which will cause the HPGe detector's resolution degeneration.
- The Kinetic Energy Released in (silicon or germanium) MAtter, or KERMA, is a good way to describe displacement damage for detector crystals.
- KERMA(keV) = $\mathrm{NIEL}\left(\frac{\mathrm{keV}*\mathrm{cm}^2}{\mathrm{g}}\right) \times \phi\left(\frac{N}{cm^2}\right) \times w(g)$

Where NIEL is Non Ionizing Energy Loss, ϕ is the cumulative neutron density and w is the mass of the material.



Angela Vasilescu and Gunnar Lindstroem's work, https://rd50.web.cern.ch/rd50/NIEL/default.html

HPGe Neutron Radiation Hardness



X axis describes the number of neutrons absorbed by HPGe detectors, Y axis describes the FWHM @ 1332 keV.

When the cumulative neutrons density arrives at 10^{10} neutron per cm^2 (Cf_{252} source), the HPGe detector's energy resolution degenerates to twice of its original resolution, which means it needs to be annealed.