Stopping Target Monitor
Mu2e Evolution to Mu2eII

David Koltick

Purdue University
Department of Physics and Astronomy

Mu2e II
Northwestern University
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Topics

1. Mu2e II STM Goals
2. HPGe
3. Compare ELBE to Mu2e
4. Experimental layout for the NaI-detector and HPGe-detector
5. Results of beam studies using an NaI detector
6. Results of beam studies using HPGe detector
7. Detector Housing for Mu2e
8. Backscatter Spectrometer for Mu2e II
9. Signal Processing Algorithms
10. Summary of Things to be done for Mu2e II

Stopping Target Monitor

General Approach

- Determine the rate of muon stops in the Stopping Target.
- Measure X-rays and Gamma rays from muon stops/captures
- Use HPGe/Other detector for the best signal to noise ratio and separation of possible background lines from signal lines.
- Determine the total luminosity to 10%

- The goal of the Mu2e experiment is to measure

$$R_{ue} = \frac{\mu,^{-}N \rightarrow e^{-}N}{\mu,^{-}N \rightarrow all\ muon\ captures}$$

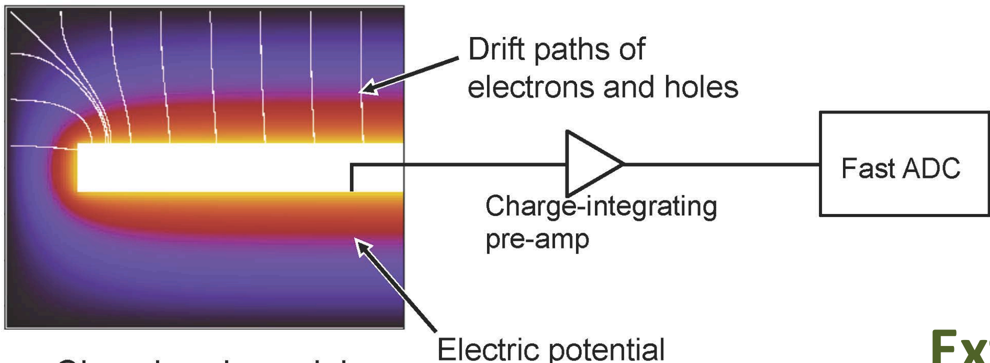
Mu2e required to measure the denominator to at least 10% Potential candidate signals include

1. Prompt: *2p* → 1s, 347 keV gamma, intensity of 79.7%
2. Prompt: *3d* → 2p, 66.1 keV gamma, intensity of 62.5%
3. Delayed: $^{27}Mg \rightarrow {}^{27}Al$, 844 keV gamma, 13% x 72% (9.5 min)
4. $^{27}Al\ (\mu,^{-}\nu n\gamma)^{26}Mg$ 1809 keV gamma, 51± 5%,

HPGe Detectors

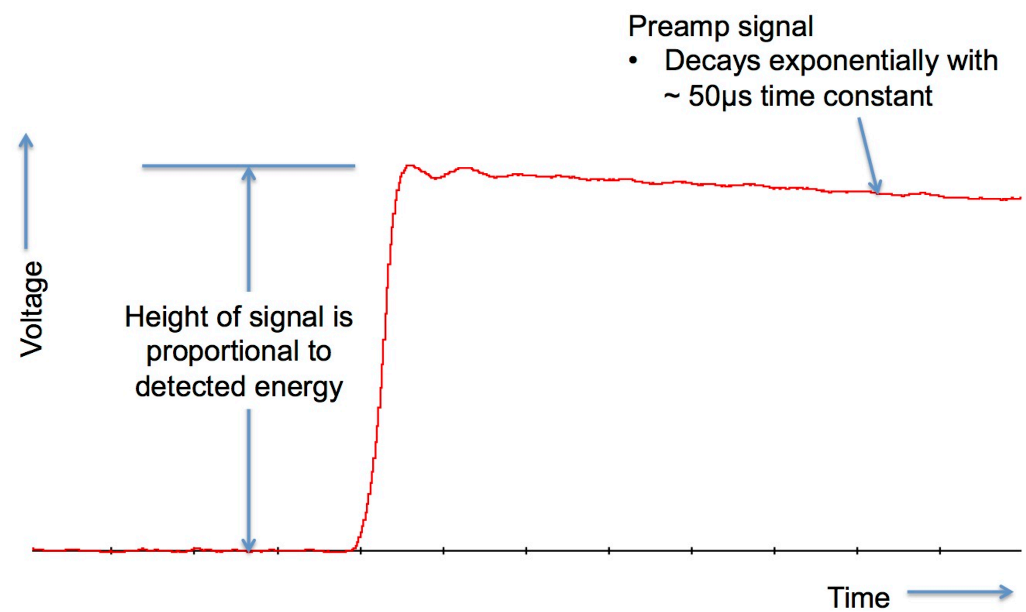
- Hyper-Pure Ge (HPGe) detectors are the “gold standard” for gamma-ray spectroscopy
  - Unsurpassed energy resolution dE/E ~0.1% at 1 MeV
  - Indispensible for nuclear structure studies for many decades
- Made from a single large crystal pulled from molten hyper-pure Ge
- Operated as a large reverse-biased diode; up to 5 kV bias
  - No current flows until a gamma ray interacts with an electron (Compton) or nucleus (pair production) in the Ge
  - This electron scatters off other electrons, creating many electron-hole pairs; each pair takes ~ 3 eV in energy
  - The electrons and holes separate in the strong electric field and are collected at the electrodes
  - The resulting charge pulse is proportional to the deposited gamma-ray energy, and is amplified and digitized
- Operated at cryogenic temperatures to prevent thermal generation of electron-hole pairs

HPGe Detectors

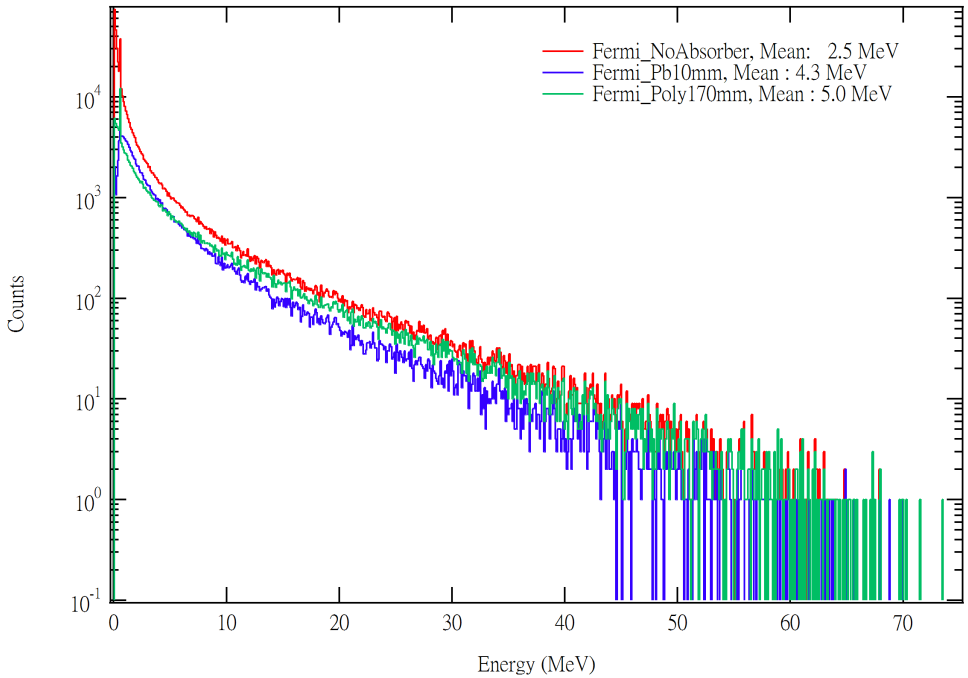


Closed-end coaxial

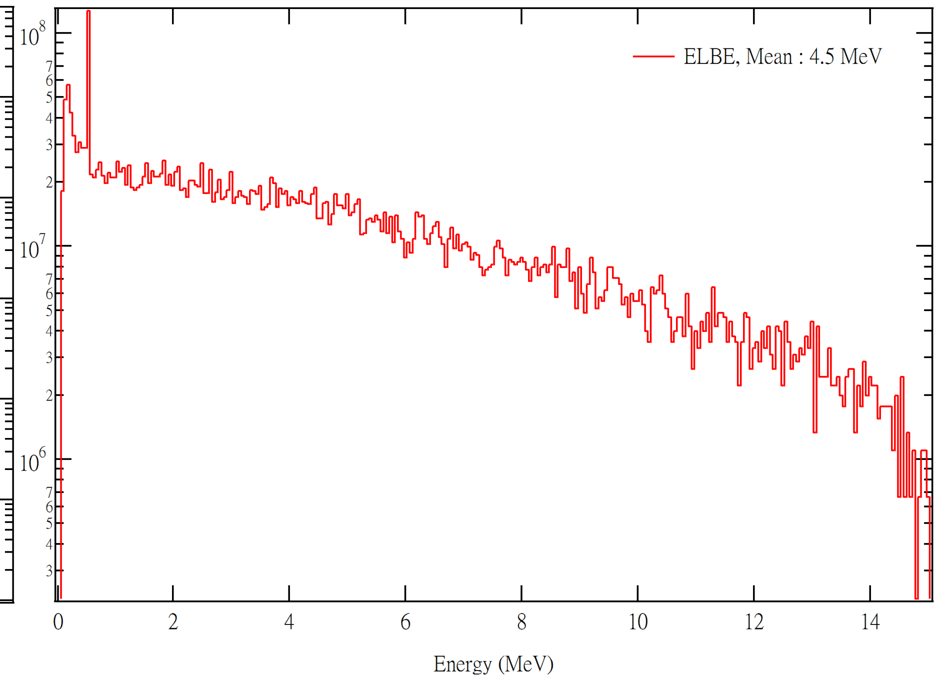
Extracting Signal Amplitude



Compare: Mu2e and ELBE



Gamma Spectrum Mu2e: Max ~75 MeV

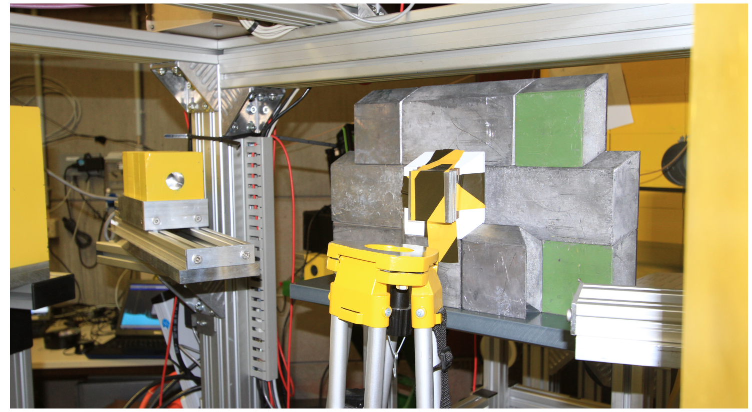


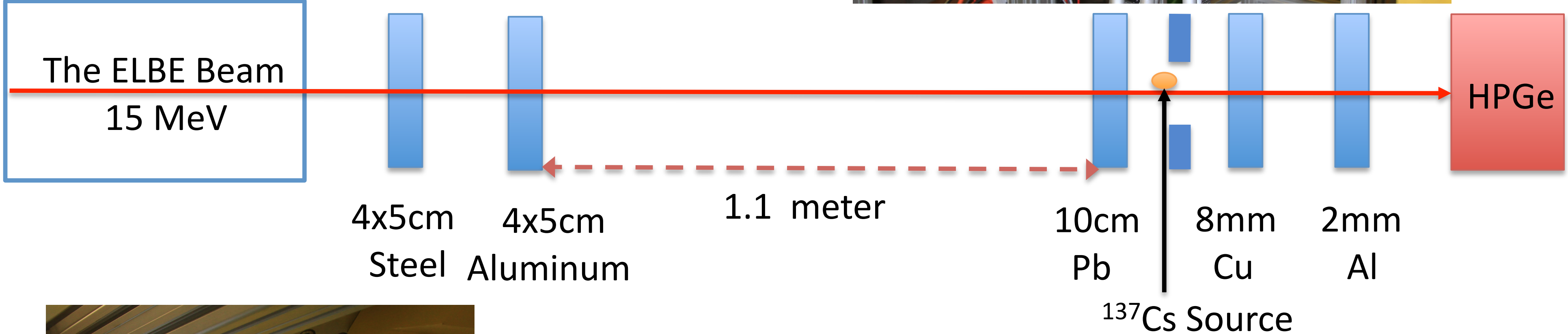
Hardened Brem Spectrum ELBE: Max 15 MeV

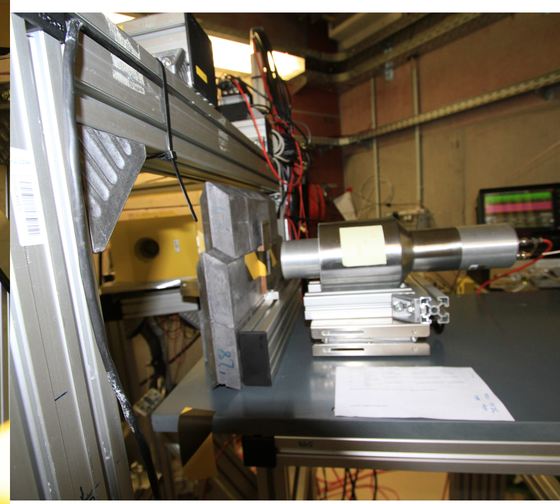
	Fermilab	ELBE
Pulse separation	1.8μ sec	2.4μ sec
Average Energy for occupied pulse	~5 MeV	~5MeV
Max Gamma Energy	75MeV	15MeV
Occupancy	20%	20%

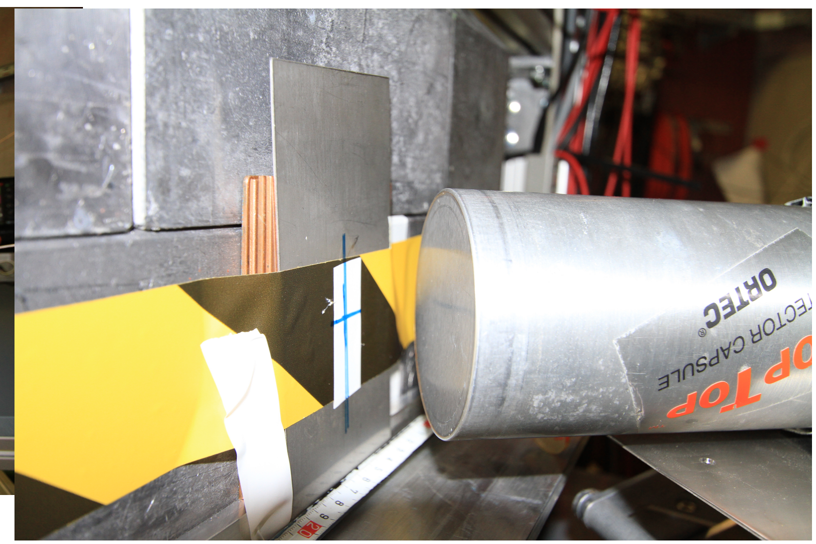
The ELBE setup (Top View)

1.2-cm diameter Aperture in Lead wall in front of HPGe

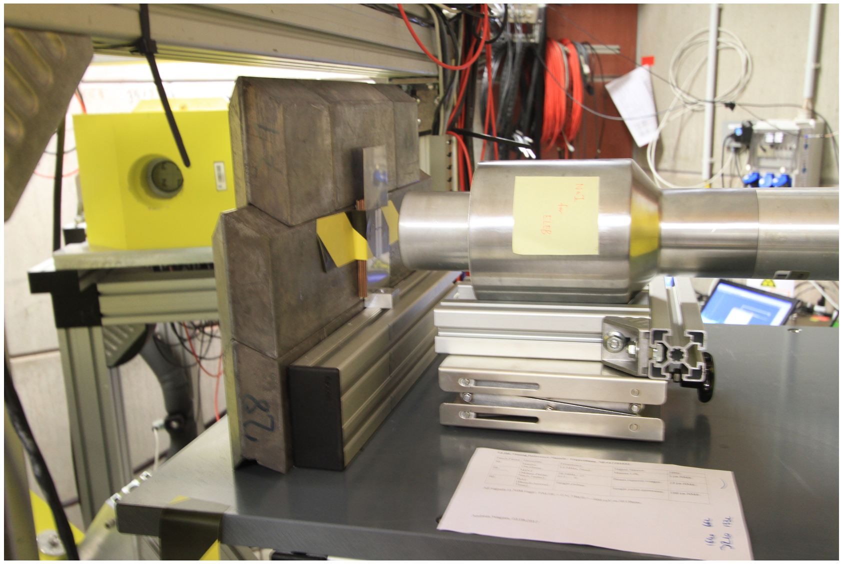








Experimental Layout: Detectors

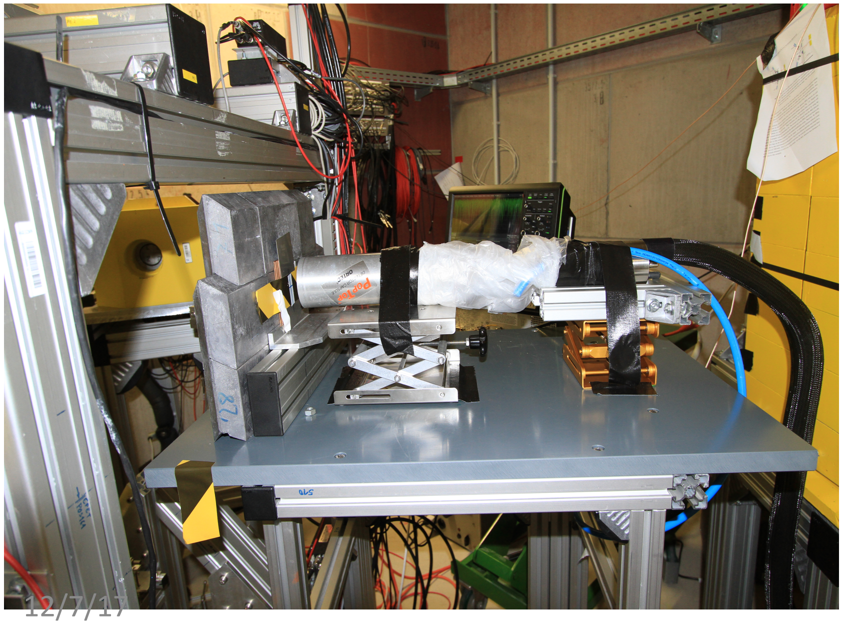


100% NaI Detector
3-inch x 3-inch Right Cylinder (Solid)

5-inch Phototube for ~250-psec timing

Cost ~$5k

Florescence time constant ~250 nsec
Has the ability to follow the beam



50% HPGe Detector
2.5-inch x 3 inch Right Cylinder

Characteristic Drift time of electron-hole
< 1 microsecond (size dependent)

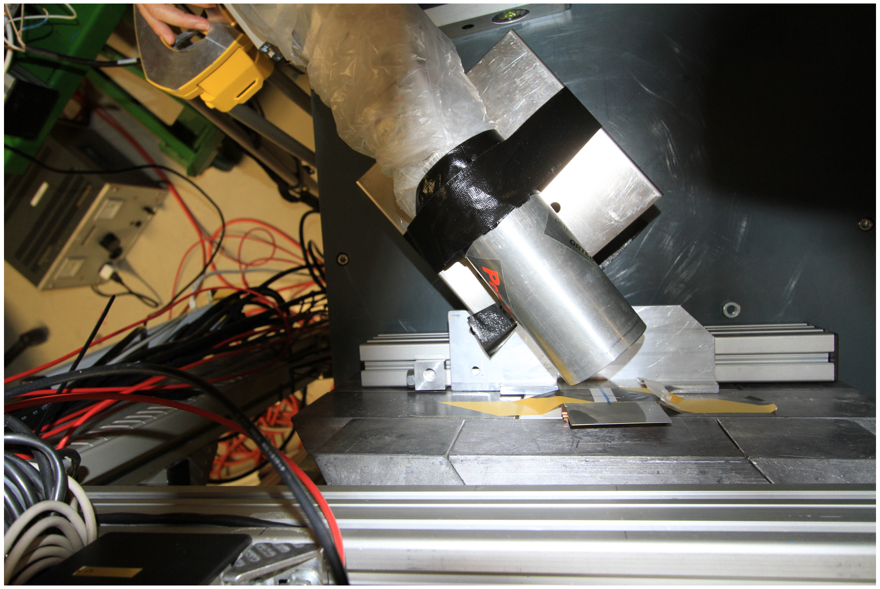
Characteristic Amplifier time constant
~50 microseconds

Timing ~ 2 nano-seconds

Will Integrate over many beam pulses

Cost ~$1k/percent ~ $60k

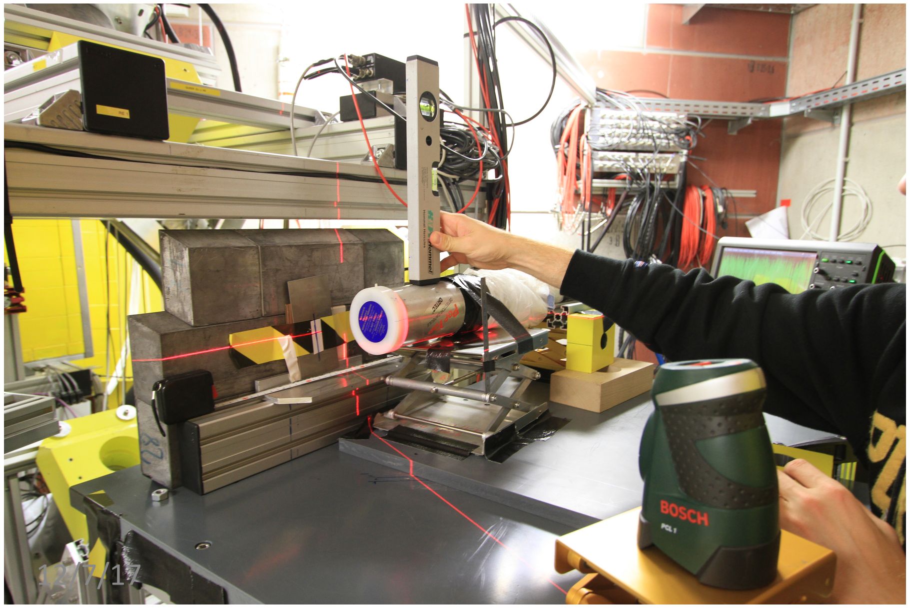
Experimental Layout: Detectors



In order to reduce the average absorbed energy the detector was placed ~45 degrees to the beam.

High Energy Brem-Gammas with forward showers would have reduced energy deposition

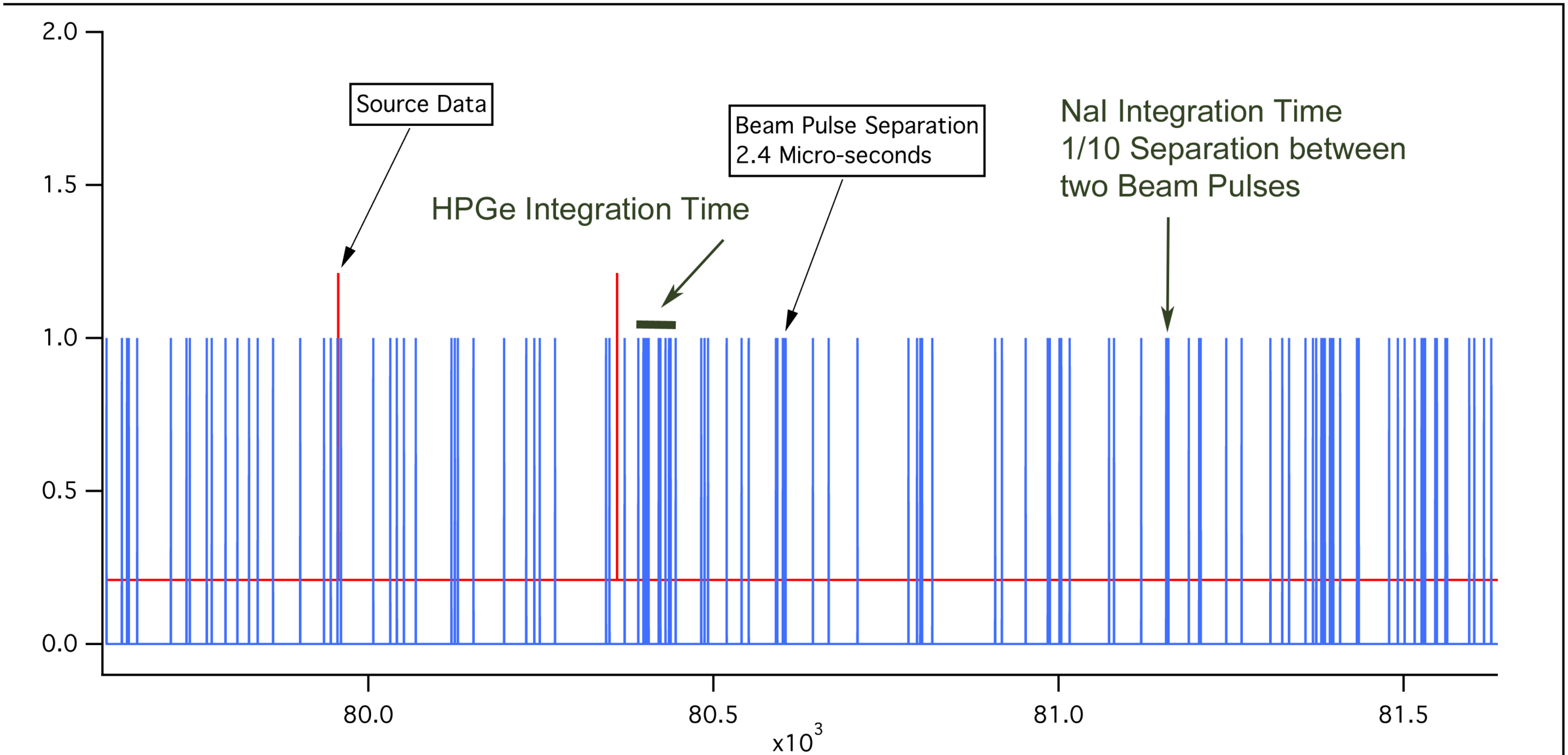
Low Energy Source-Gammas 100keV to 2 MeV have full acceptance.



HPGe Detector was placed at 90 degrees to the check its response.

The response was similar to the Face-on to the beam response.

Experimental Layout: Important Parameters

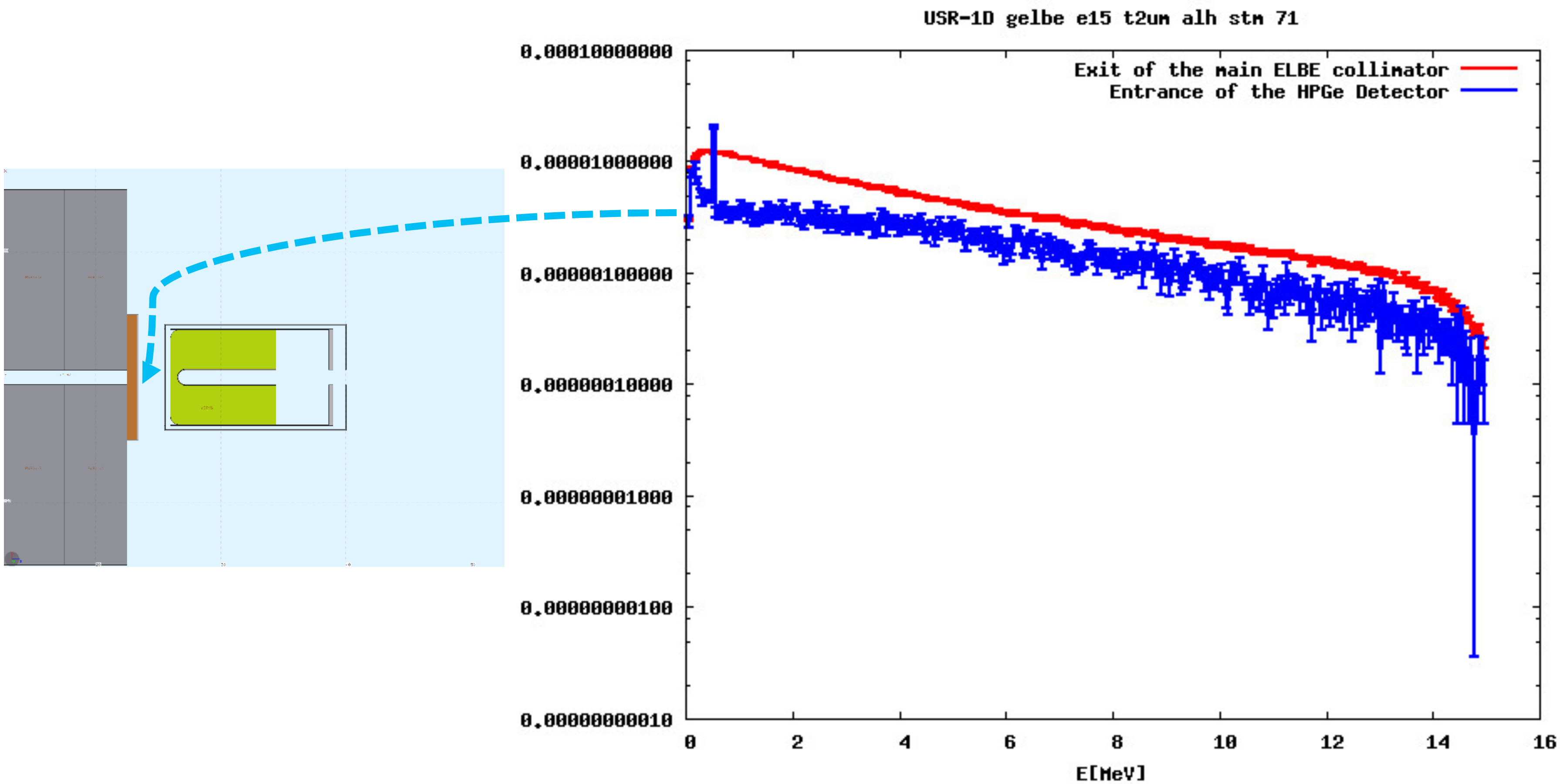


Beam Occupancy: Probability that a Beam Pulse has a Gamma Ray (Set by Main Machine Current)

Average Beam Pulse Energy: (Hardened Beam ~5 MeV)

Max Beam Energy: 15 MeV (ELBE)

Bremsstrahlung spectra

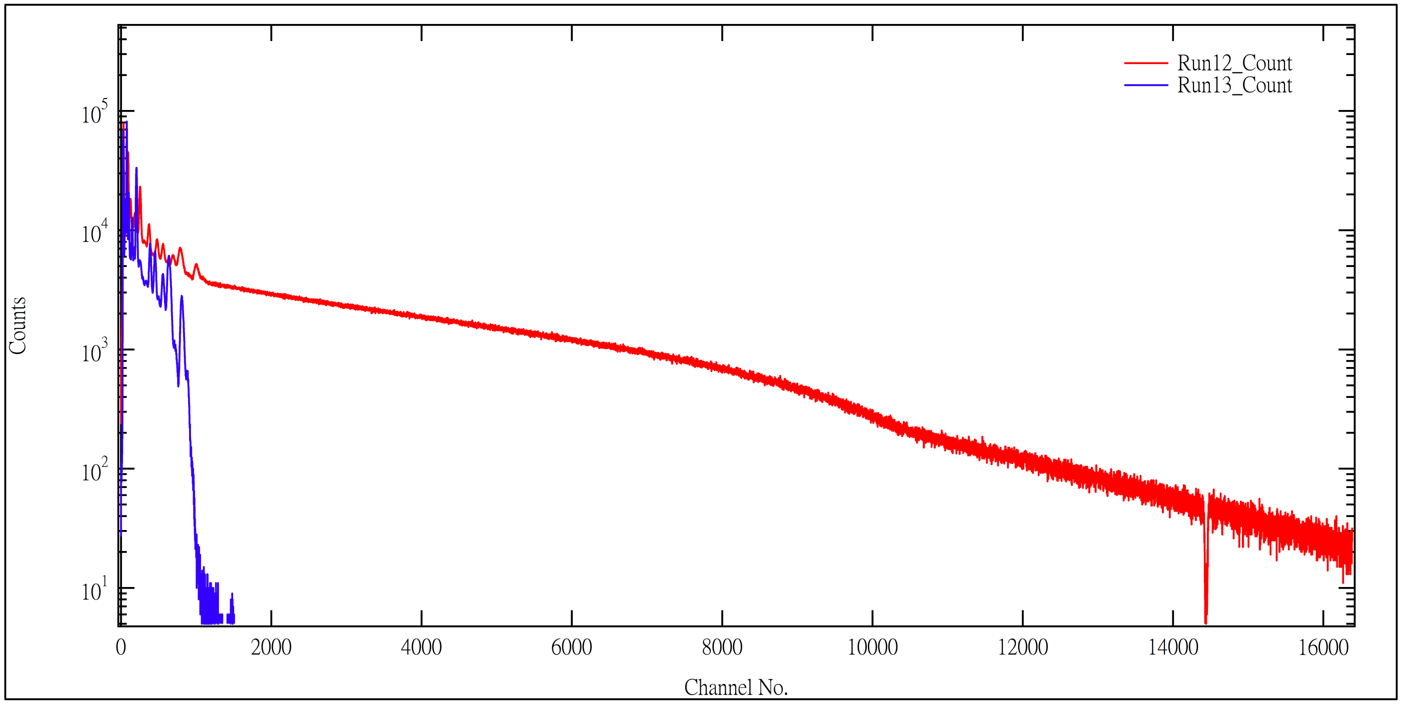


Hardened Spectrum

Drops by 5 between ~1MeV and 10MeV

Average Pulse Energy between ~5 MeV or higher

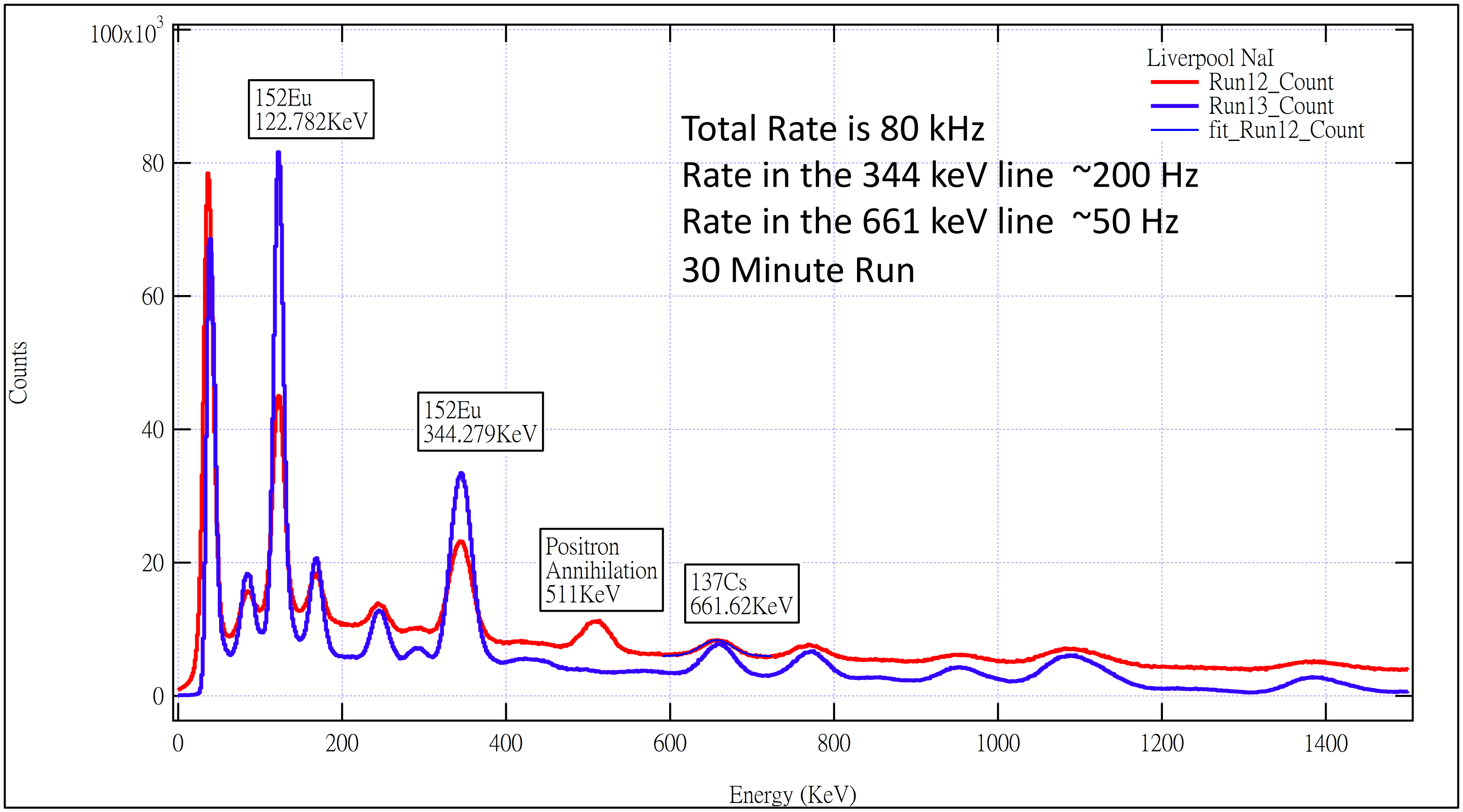
Studies Using NaI detector



The end point is estimated to be 22.4 MeV using a linear calibration ~1.4 keV/bin

Indication of multiple gamma per pulse which increases the required dynamic range of the DAQ

Studies Using NaI detector

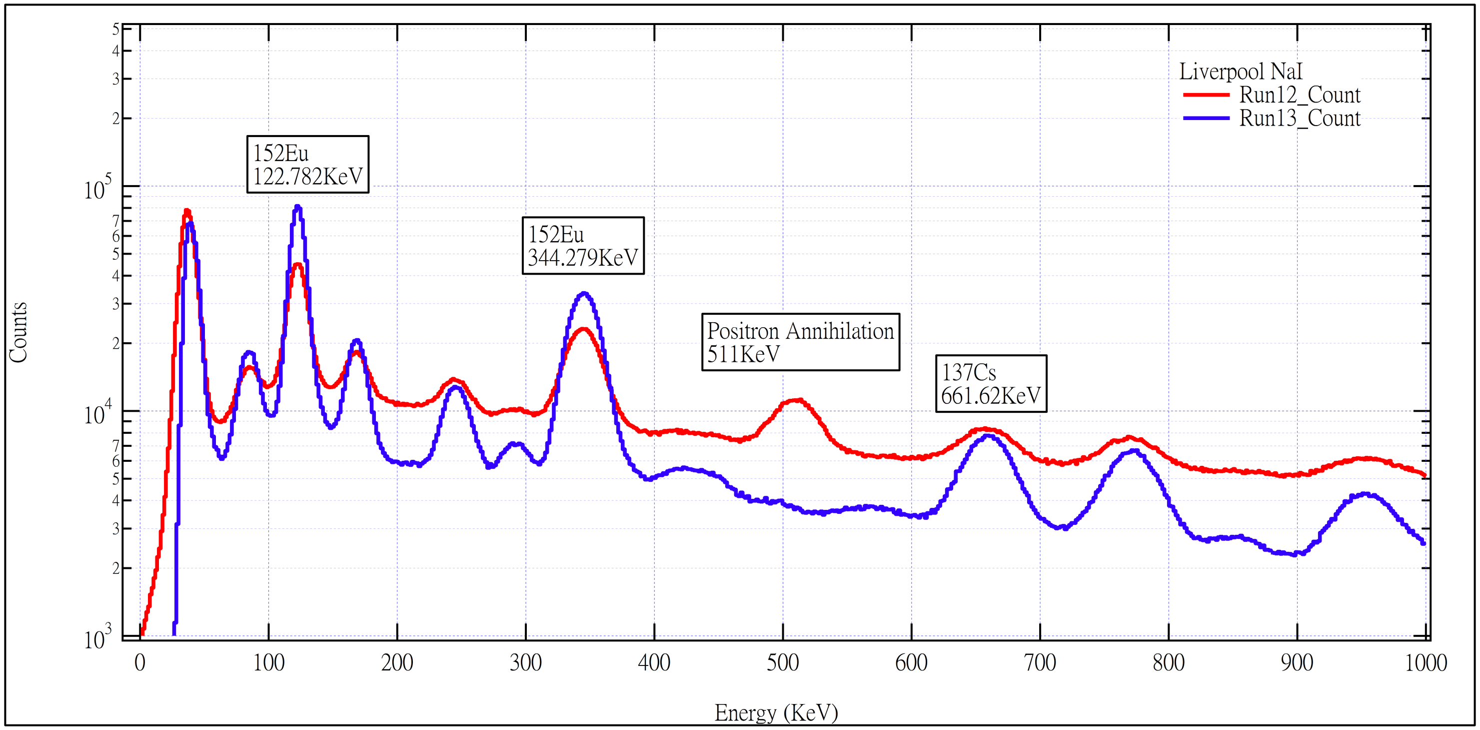


The Lines have good Significance $Sig_{Cs} \sim 2\text{x}10^3$ $Sig_{Eu} \sim 2\text{x}10^3$

Significance

Run 12 Beam on Run 13 Beam off

NaI detector



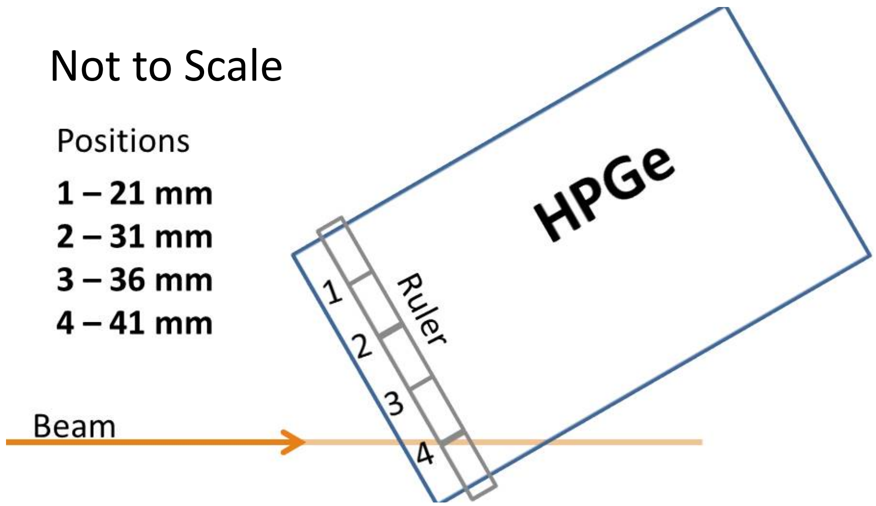
Linear Scale Run 12 Beam on Run 13 Beam off

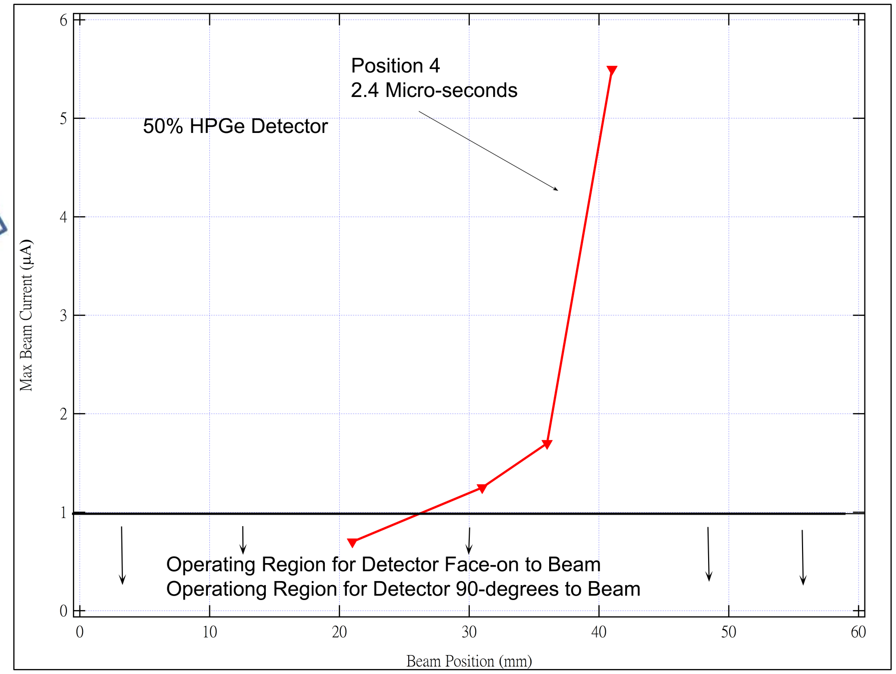
Studies Using HPGe Detector

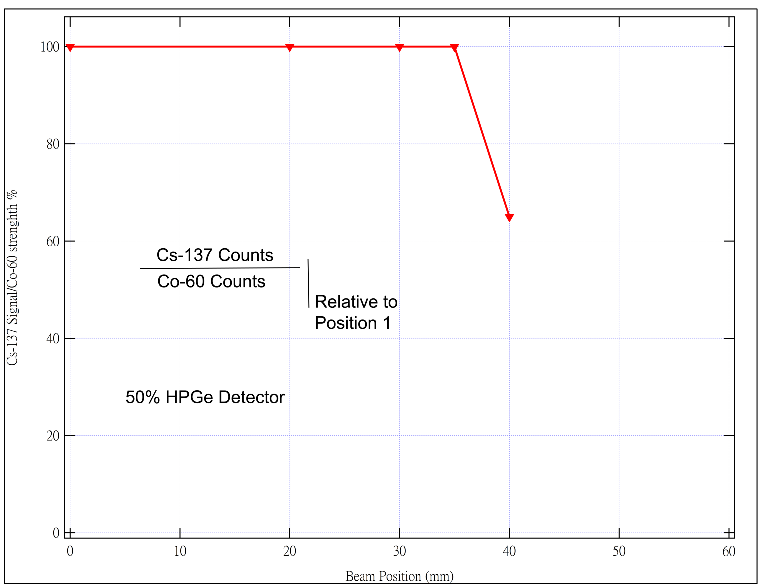
Not to Scale

Positions

1 – 21 mm
2 – 31 mm
3 – 36 mm
4 – 41 mm



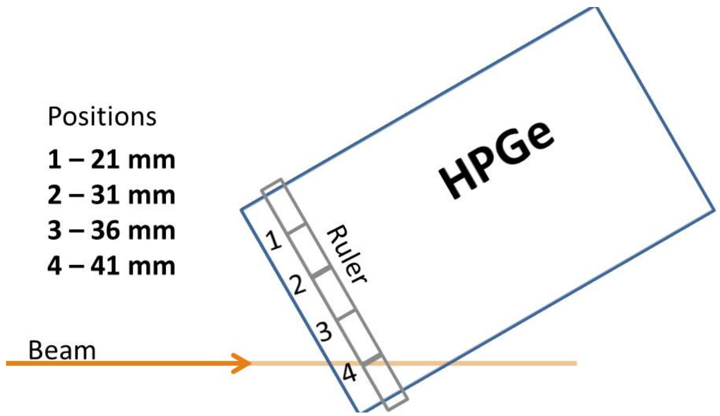




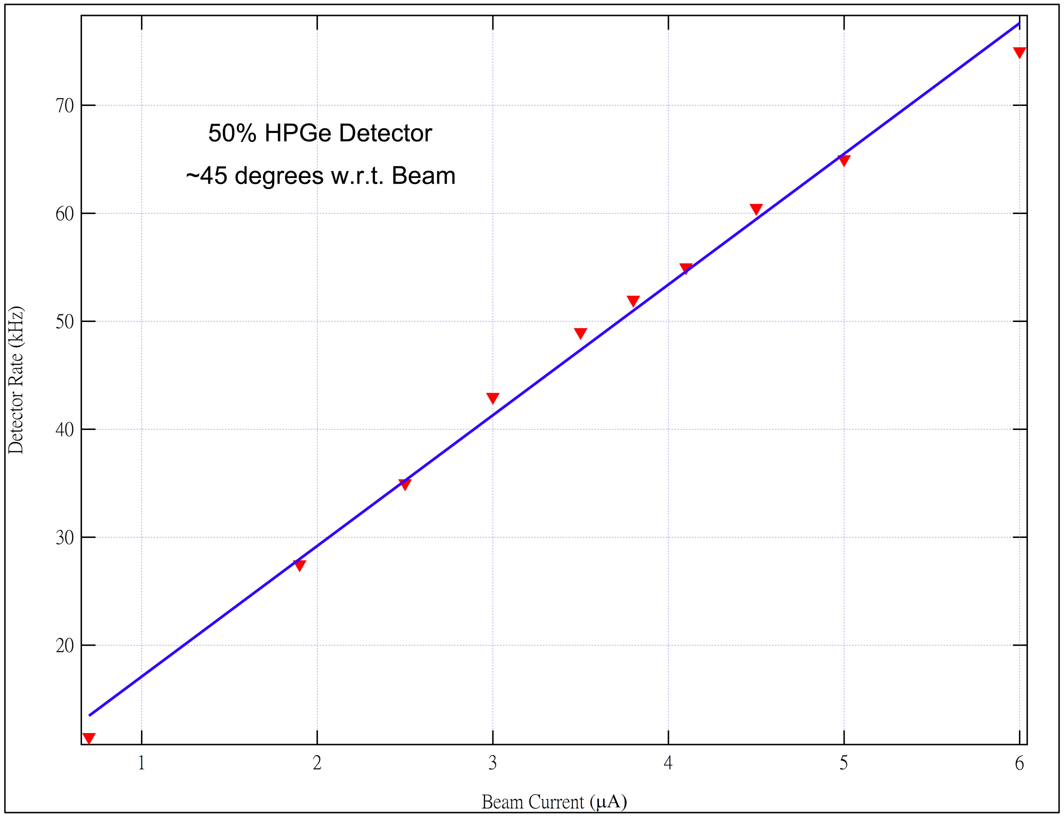
Relative Reconstruction Efficiency

Cs-source fixed behind the Pb-aperature
Co-source fixed to HPGe stand → no relative Motion

Studies Using HPGe Detector



Cs-source fixed behind the Pb-aperture
Co-source fixed to HPGe stand → no relative Motion

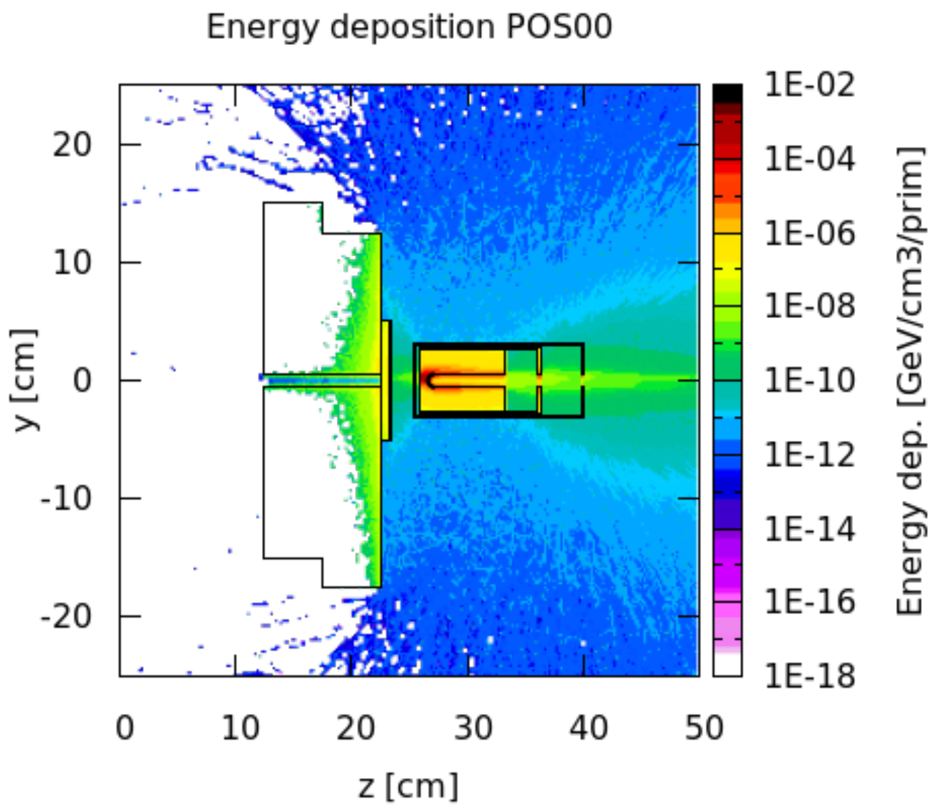


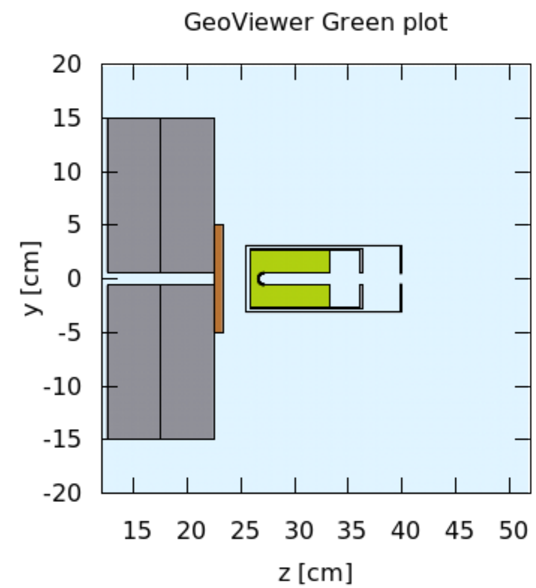
Linear Response to the high currents shows the detectors and Reconstruction algorithm are following the beam

Scaling Arguments should work

HPGe Monte Carlo Prediction to Brem-Beam

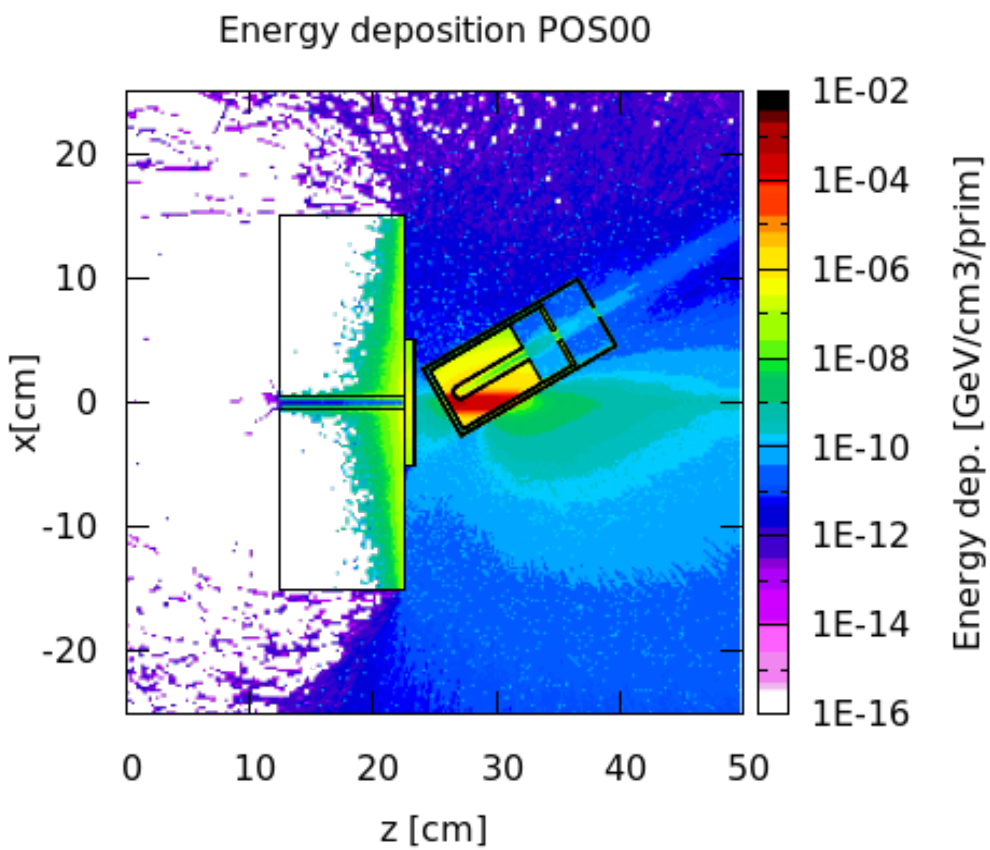
Pos00:

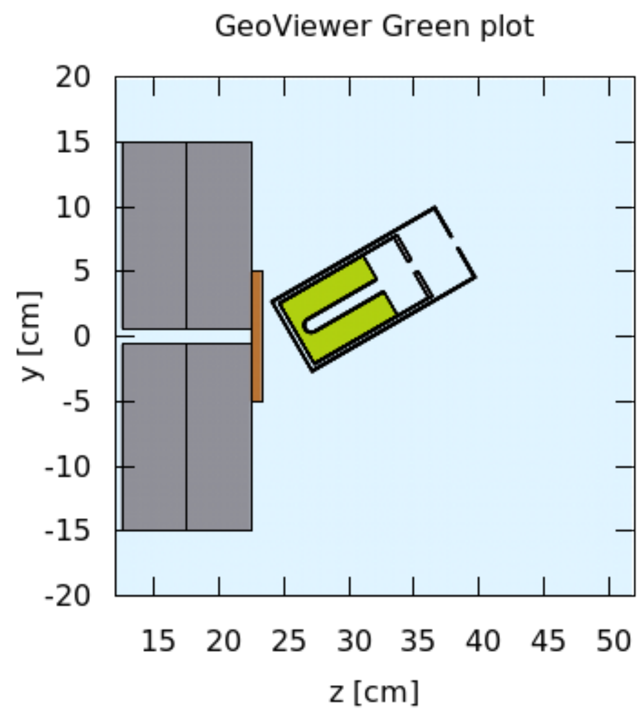




Total energy deposition in crystal:

Pos01:

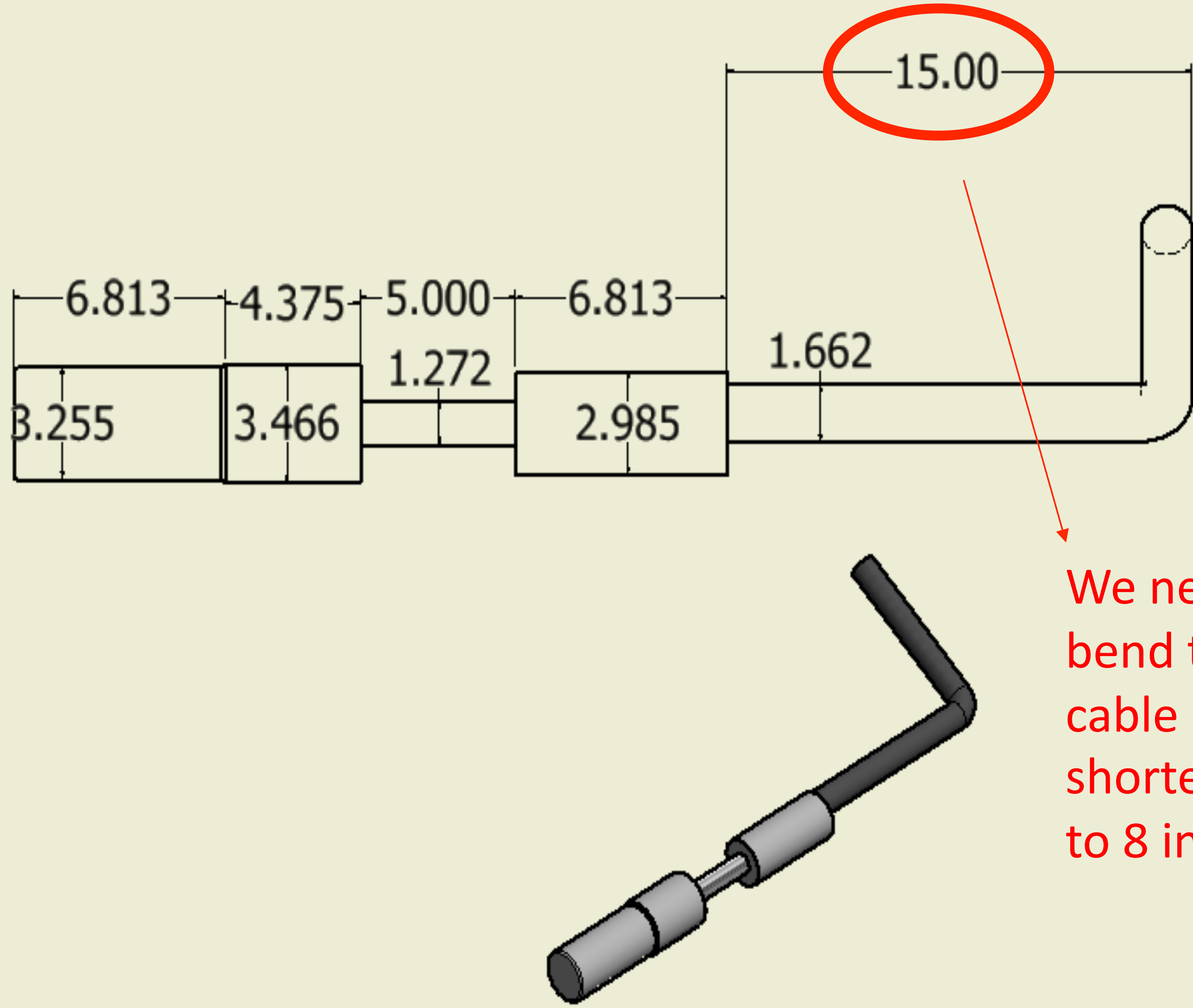




Total energy deposition in crystal:

The design of Shielding house for $HPGe$ and $LaBr_3$ detectors

60% HPGe detector Used in the design



We need to bend the cable and shorten it to 8 in

The $LaBr_3$ Detecter

Model	Base OD	PMT OD	Detector Housing OD	Detector Housing Length	Overall Length	Net Weight	Shipping Weight
LABR-1X1	57 mm 2.2 in	44.5 mm 1.8 in	30.4 mm 1.2 in	26.1 mm 1.0 in	143 mm 5.6 in + pins	~1.08 lb	20 lb
LABR-1.5X1.5	58.7 mm 2.3 in	58.7 mm 2.3 in	43.1 mm 1.7 in	39 mm 1.5 in	151.5 mm 6.0 in + pins	~2 lb	20 lb
LABR-2X2	58.7 mm 2.3 in	58.7 mm 2.3 in	55.8 mm 2.2 in	51.5 mm 2.0 in	164 mm 6.5 in + pins	~3 lb	20 lb
LABR-3X3	58.7 mm 2.3 in	58.7 mm 2.3 in	82.5 mm 3.2 in	157 mm 6.2 in	194 mm 7.6 in + pins	~6 lb	25 lb

Improved Resolution and Efficiency

As shown in Figure 1, LaBr provides better resolution performance over NaI(Tl) systems by approximately a factor of 2. Note that neither the NaI(Tl) detectors nor the lanthanum bromide detectors can approach the resolution of a HPGe detector.

The efficiency for LaBr is about 1.3 times that of NaI(Tl) for the same volume and the decay time constant is slightly more than 10% of the NaI detector decay time (see Table 1). On the basis of photoelectron yield, LaBr has higher efficiency and temperature stability than NaI(Tl).

High Count Rate Compatibility

Lanthanum bromide detectors can operate over wide dynamic ranges of count rate with little variation in energy resolution.

Figures 2 and 3 show high rate performance of a LaBr detector with an ORTEC digiBASE.

The digiBASE shows minimal resolution degradation over a wide range of count rates.

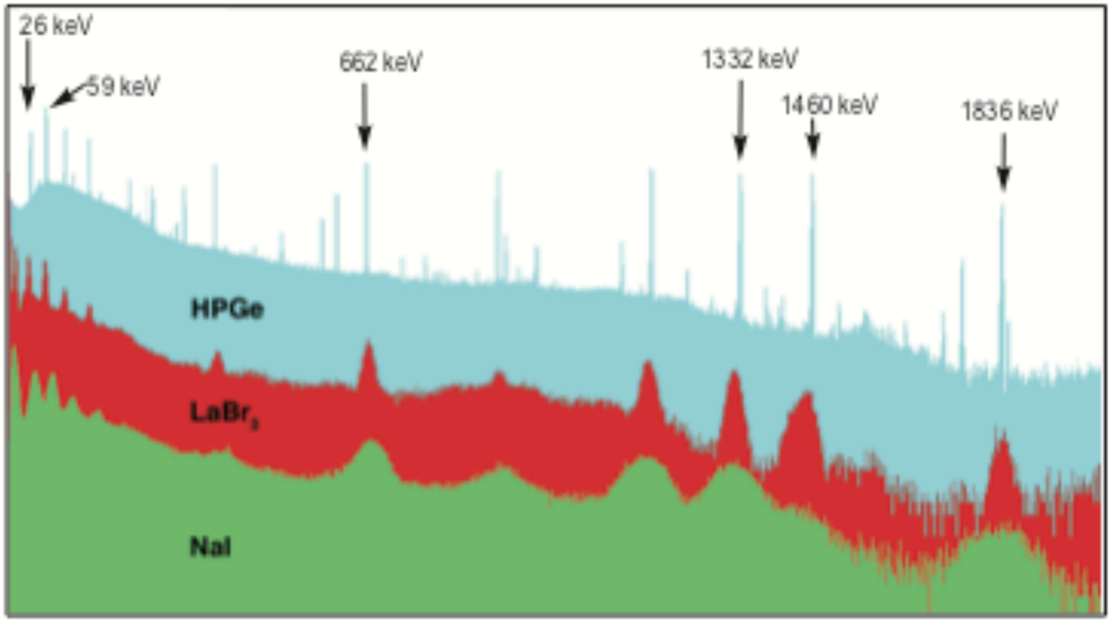


Figure 1. Comparison for $LaBr_3$(Ce), NaI(Tl), and HPGe spectra.

Table. 1. Comparison of Critical Parameter for Lanthanum Bromide Detectors.

Detector Type	Resolution @662 keV (%)	Density (g/cc)	Photoelectron Yield Relative to NaI	Primary Decay Time (□sec)
$LaBr_3$(Ce)	2.8–4.0	5.29	130	0.026
NaI(Tl)	7	3.7	100	0.230
HPGe	0.2 (1.3 keV)	5.35	N/A	N/A

Lanthanum Bromide

Scintillation Detectors

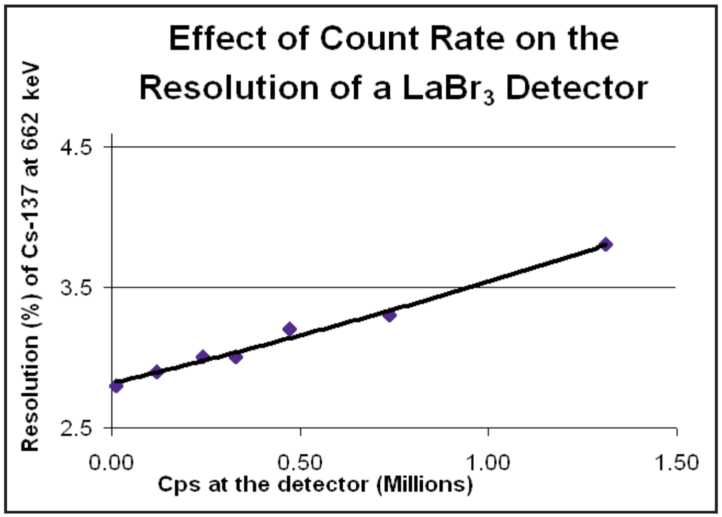


Figure 2.

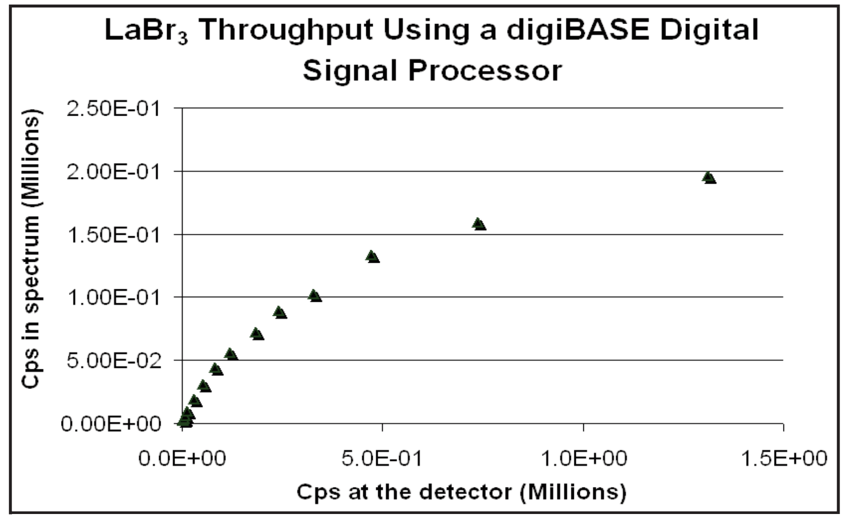
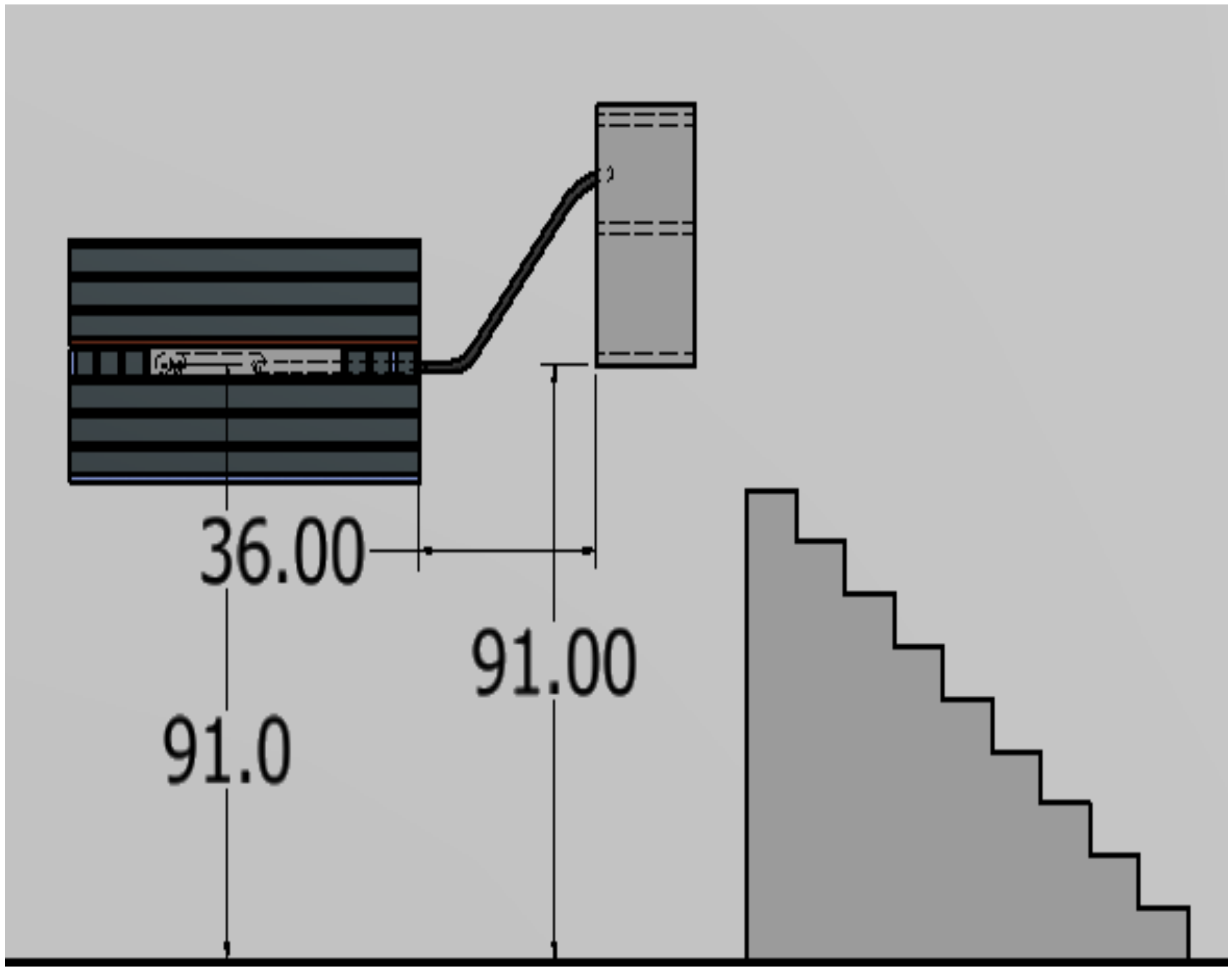


Figure 3.

Elements



Assume that this is NOT a passageway and can be blocked
Two Access step ladders that allow forward walk down

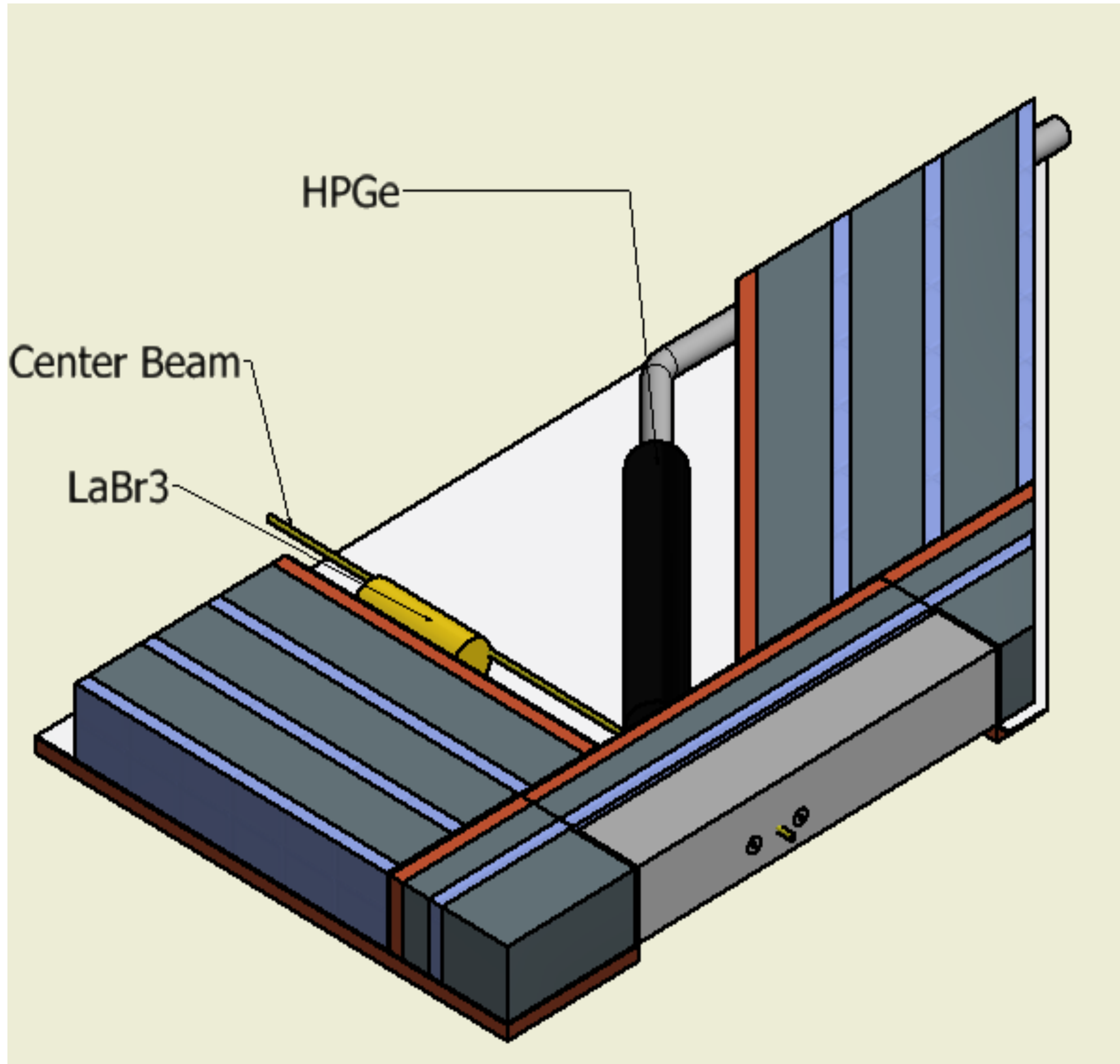
The shield for two detectors

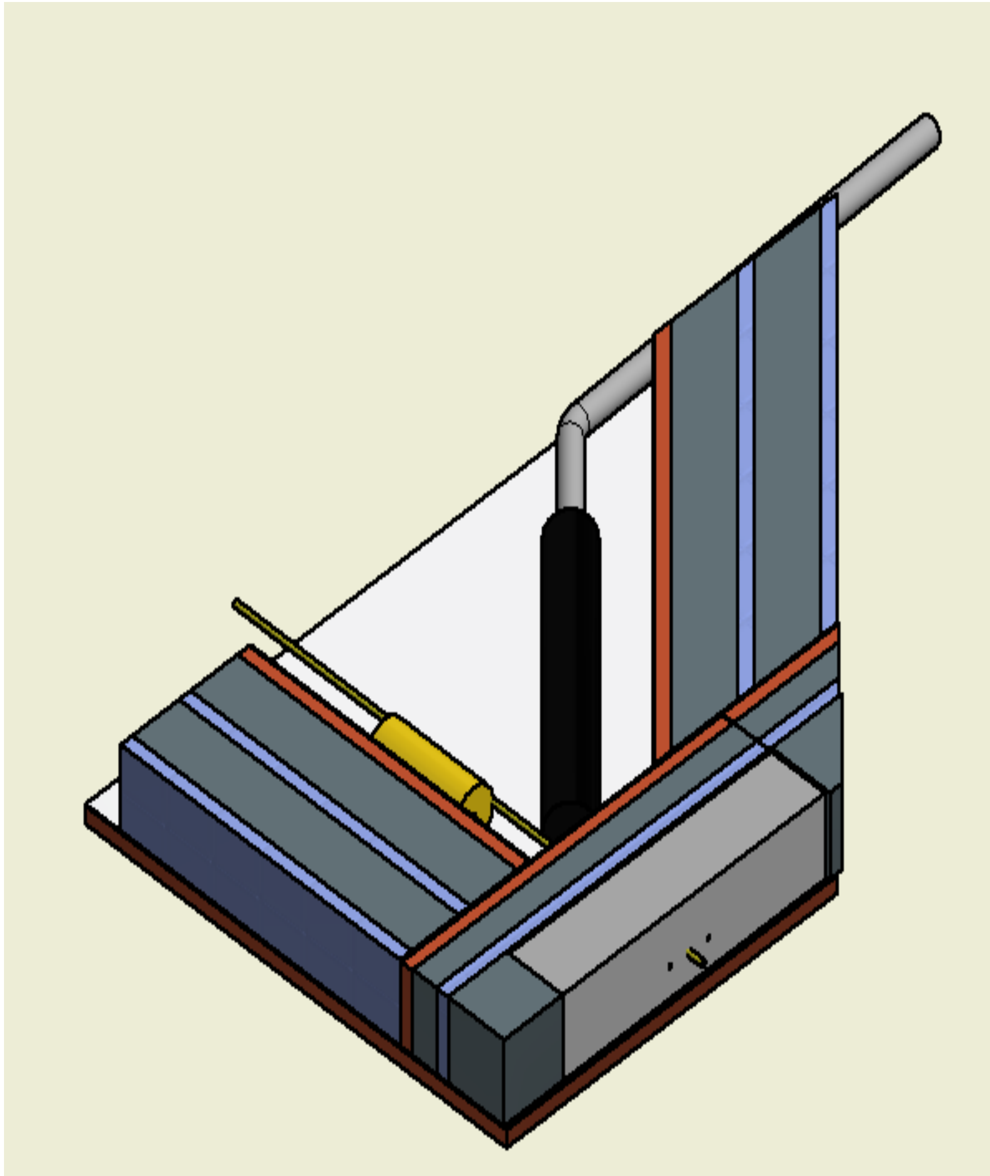
- 2 cm lead
- 1 cm copper
- 0.1 cm Aluminum

Detector Layout

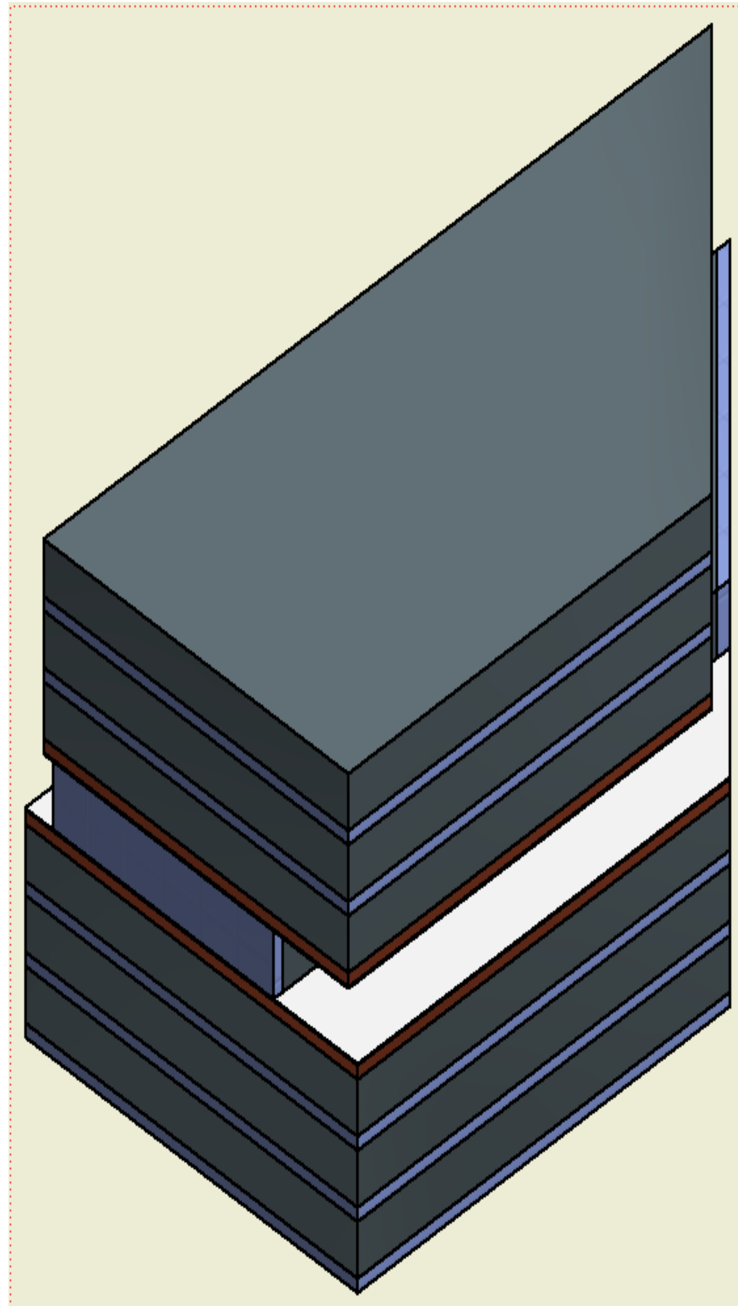
To stop Cross Talk from Compton and showering events shielding will be placed between the detectors

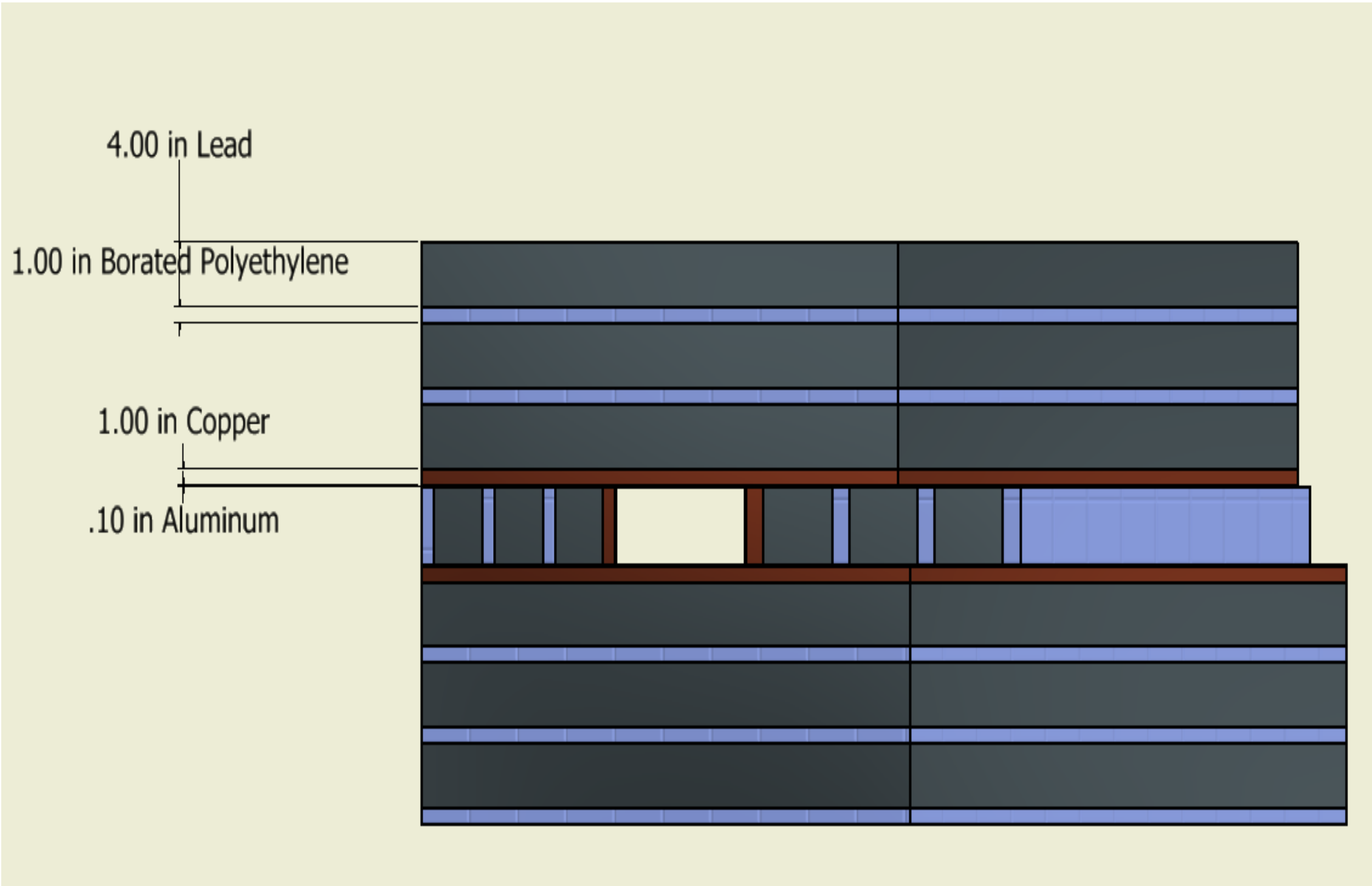
Assumption: Detector placement accuracy ~5mm.



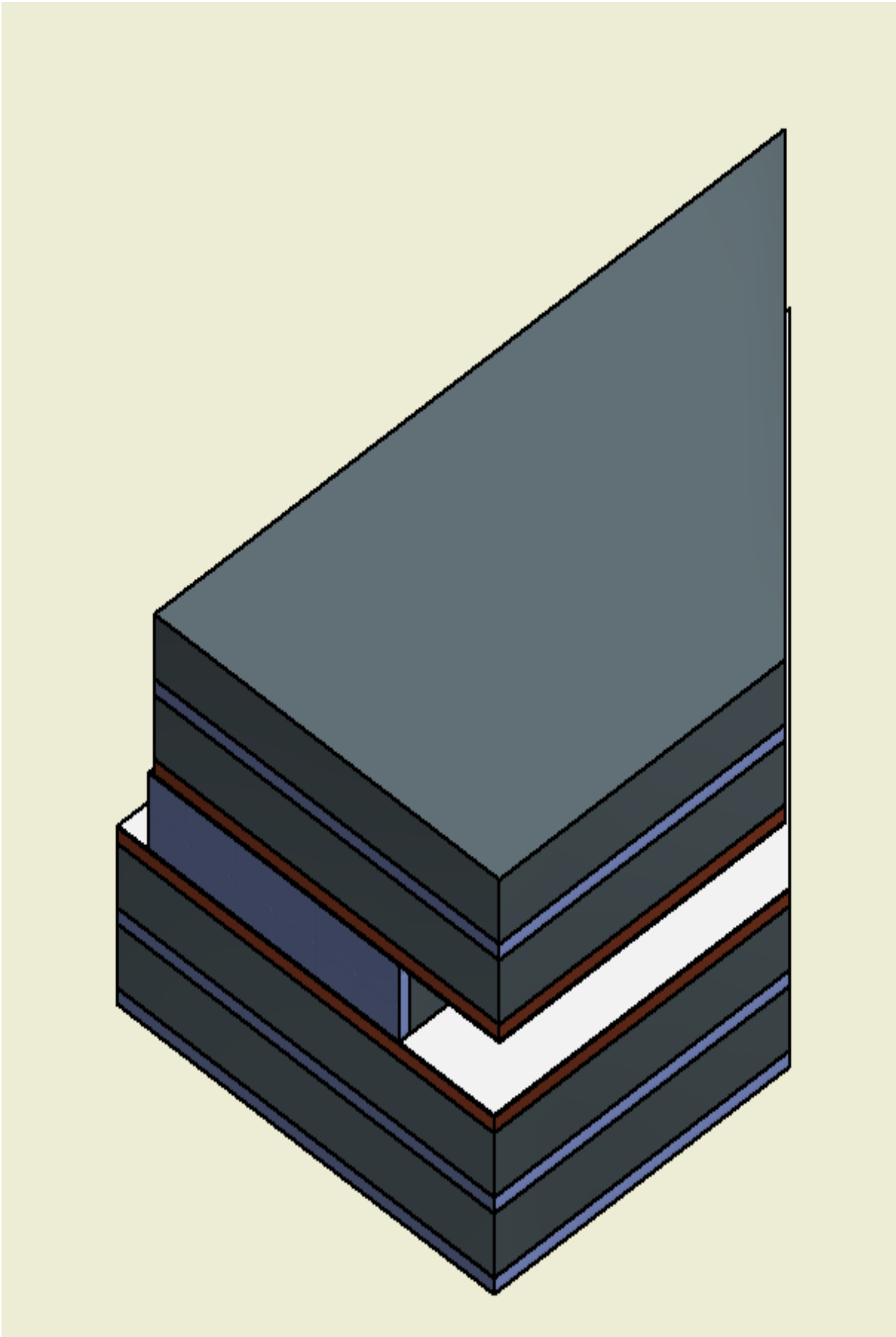


Shielding Plan1



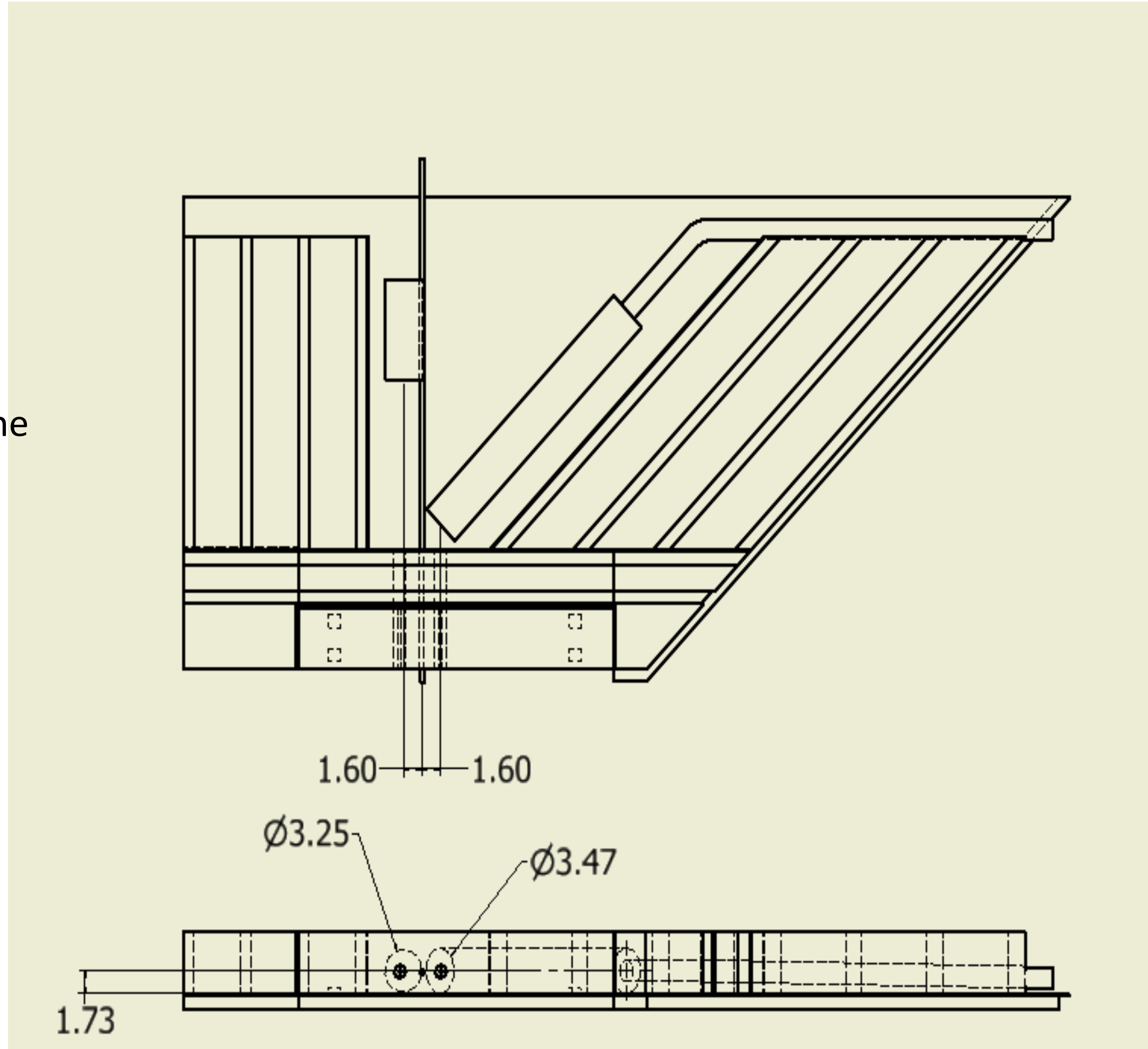

4.00 in Lead
1.00 in Borated Polyethylene
1.00 in Copper
.10 in Aluminum

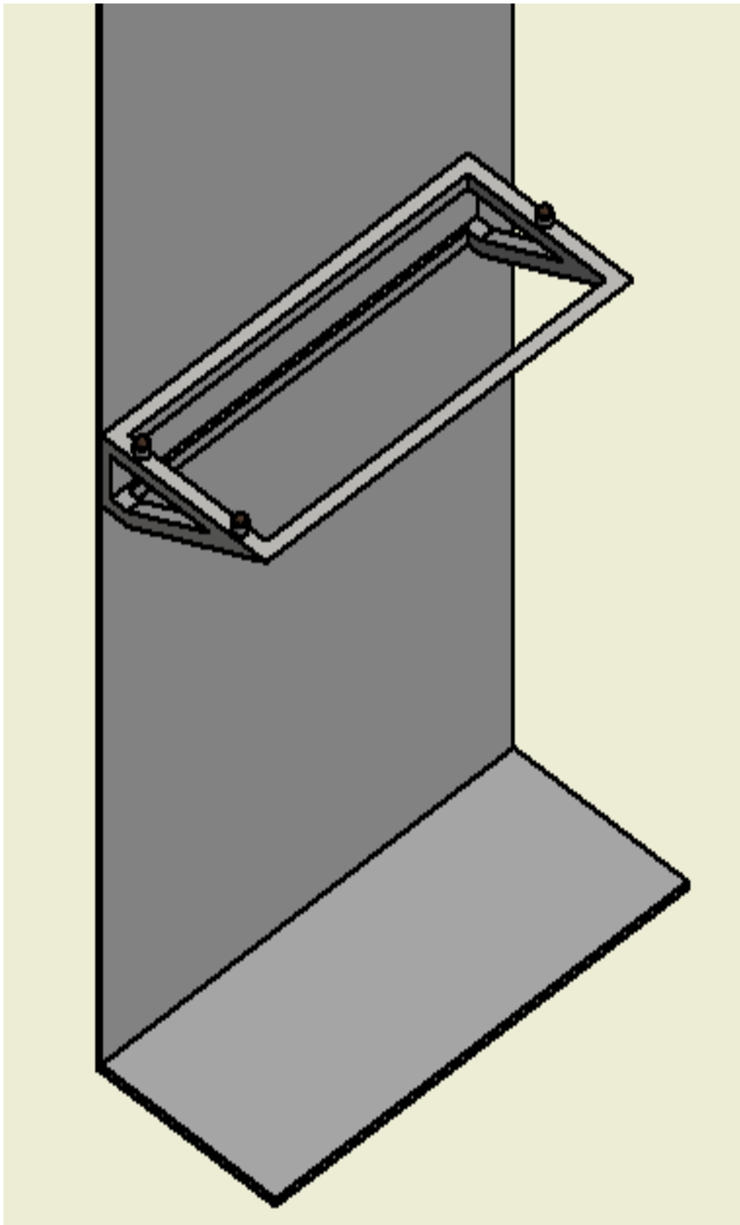
Shielding Plan2



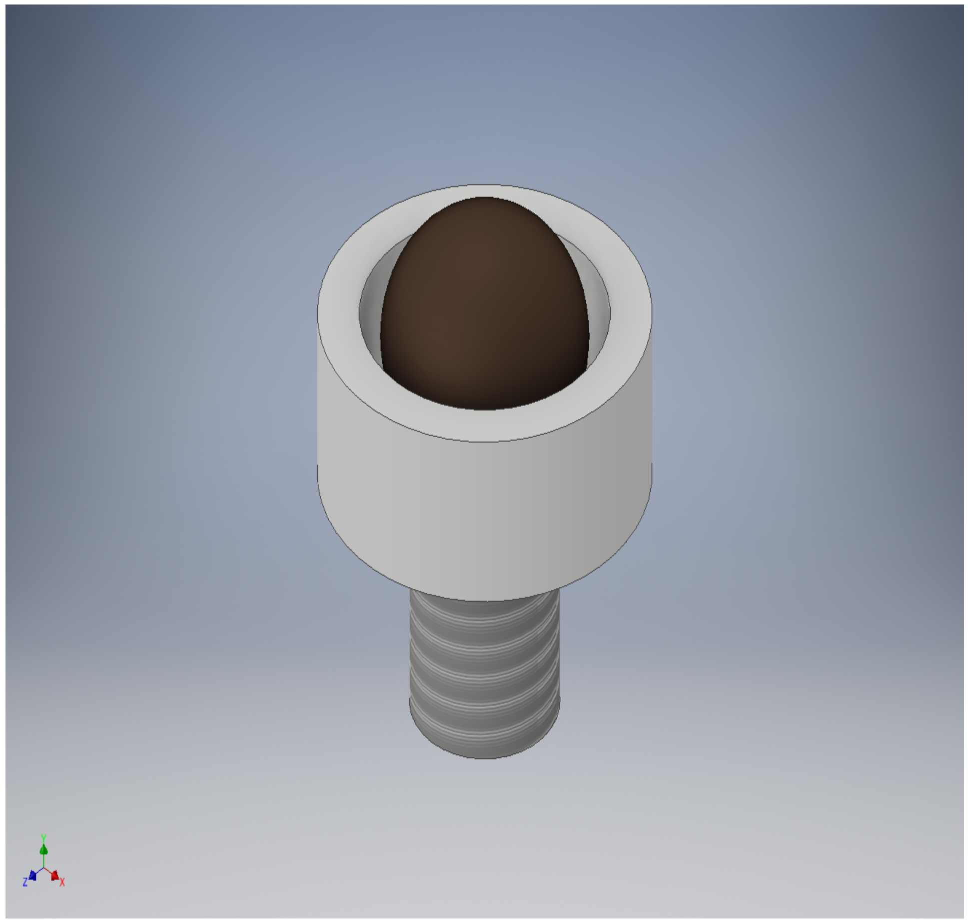
Assumption:
The HPGe Detector will not directly look at the stopping Target

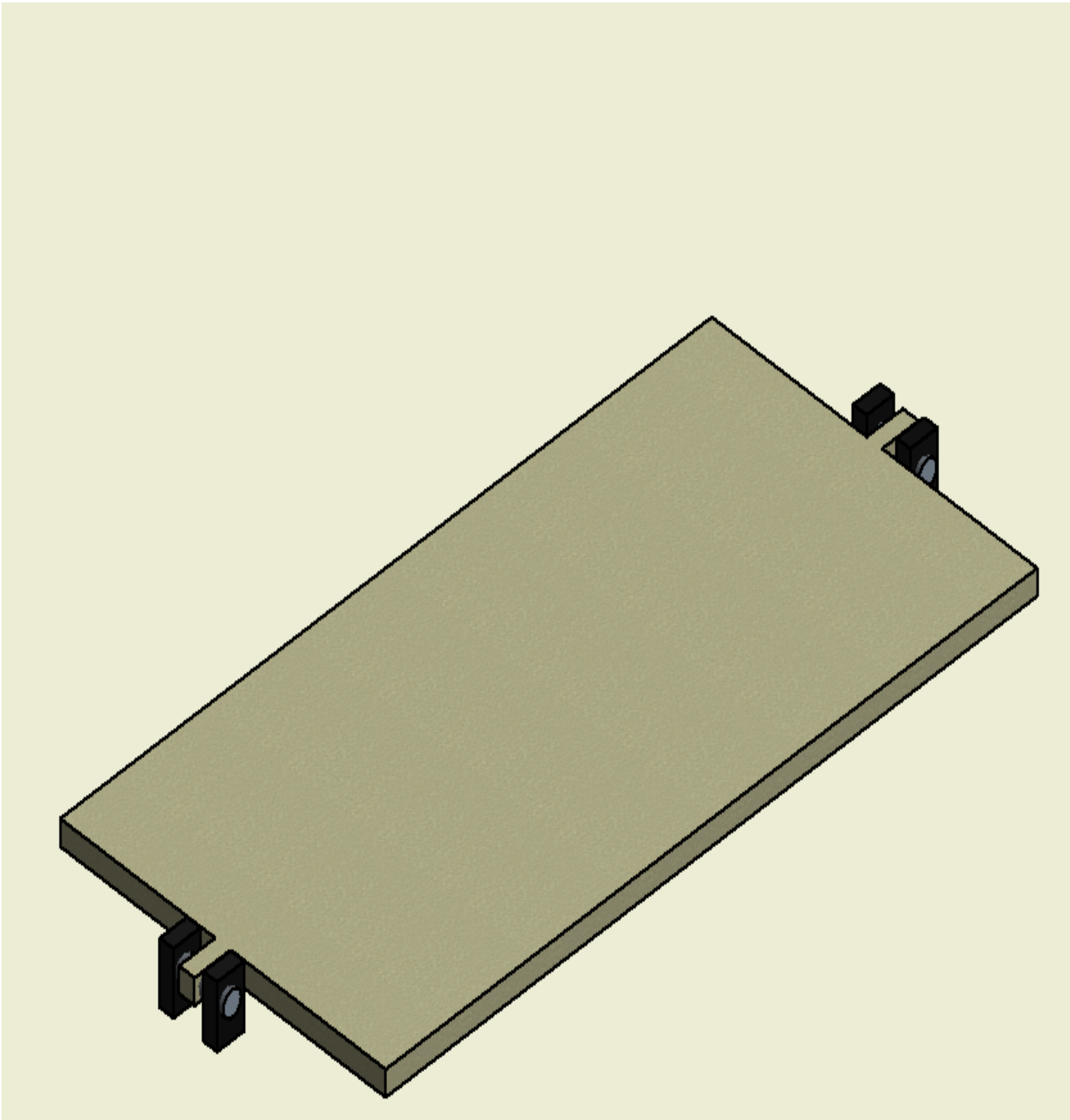
A LiBr3 Detector will be used to follow the beam





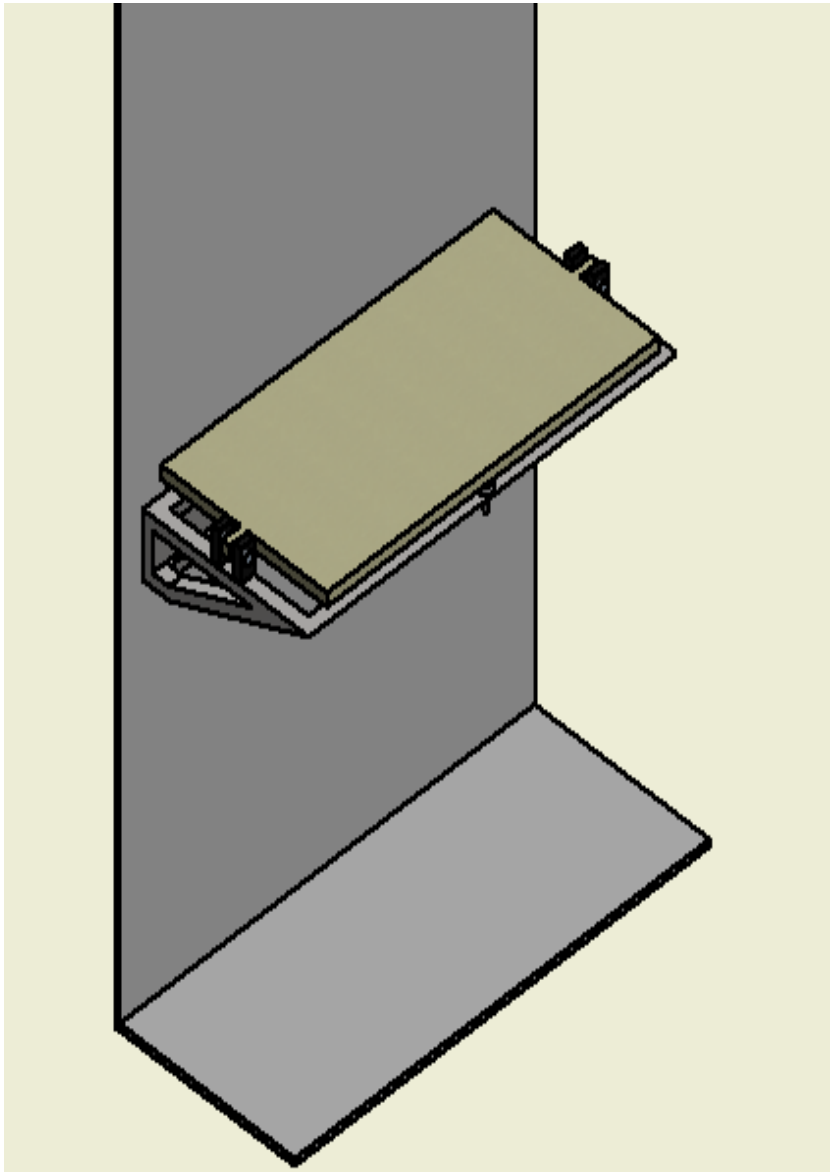
Gross Adjustment

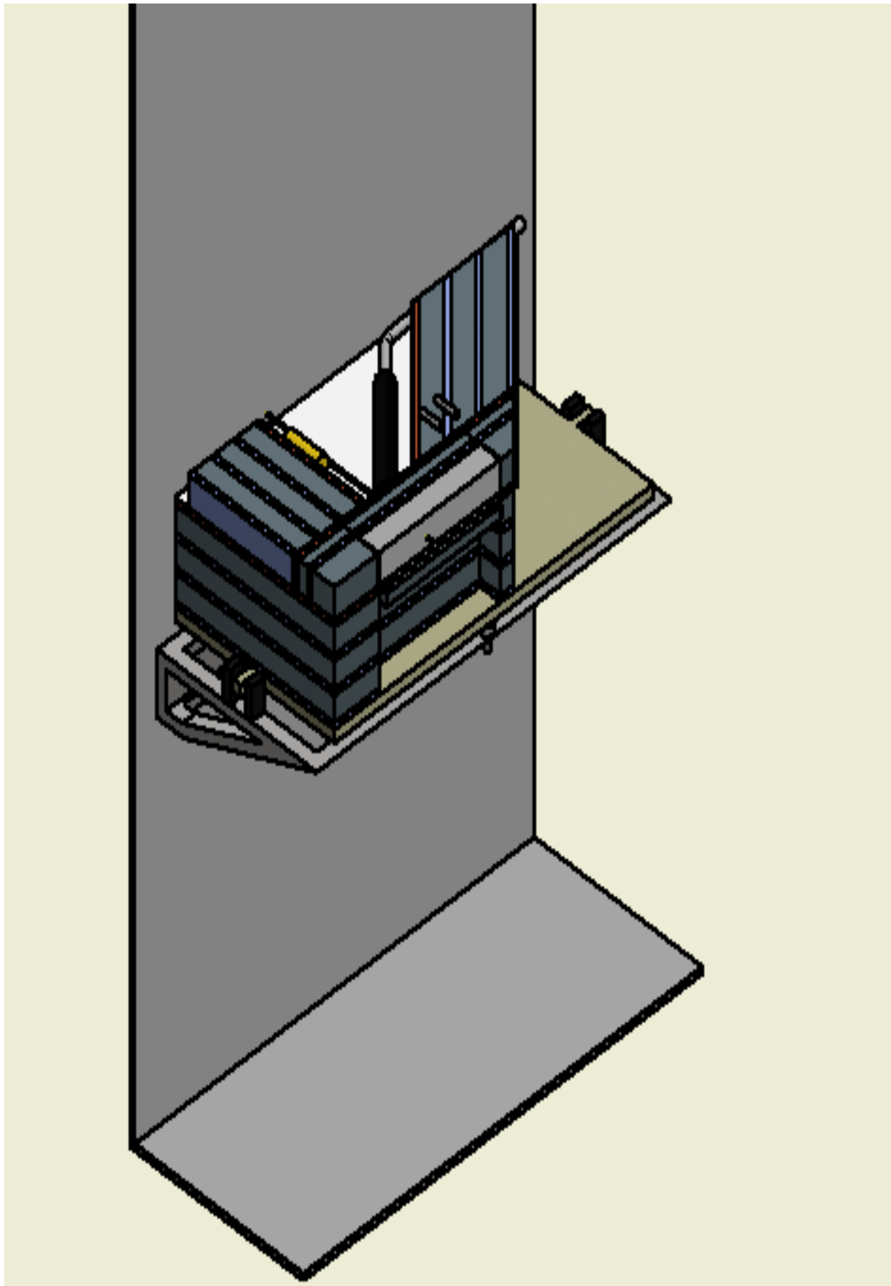




Allows
(1) Up down motion
(2) Tilt forward backward
(3) Tilt left right

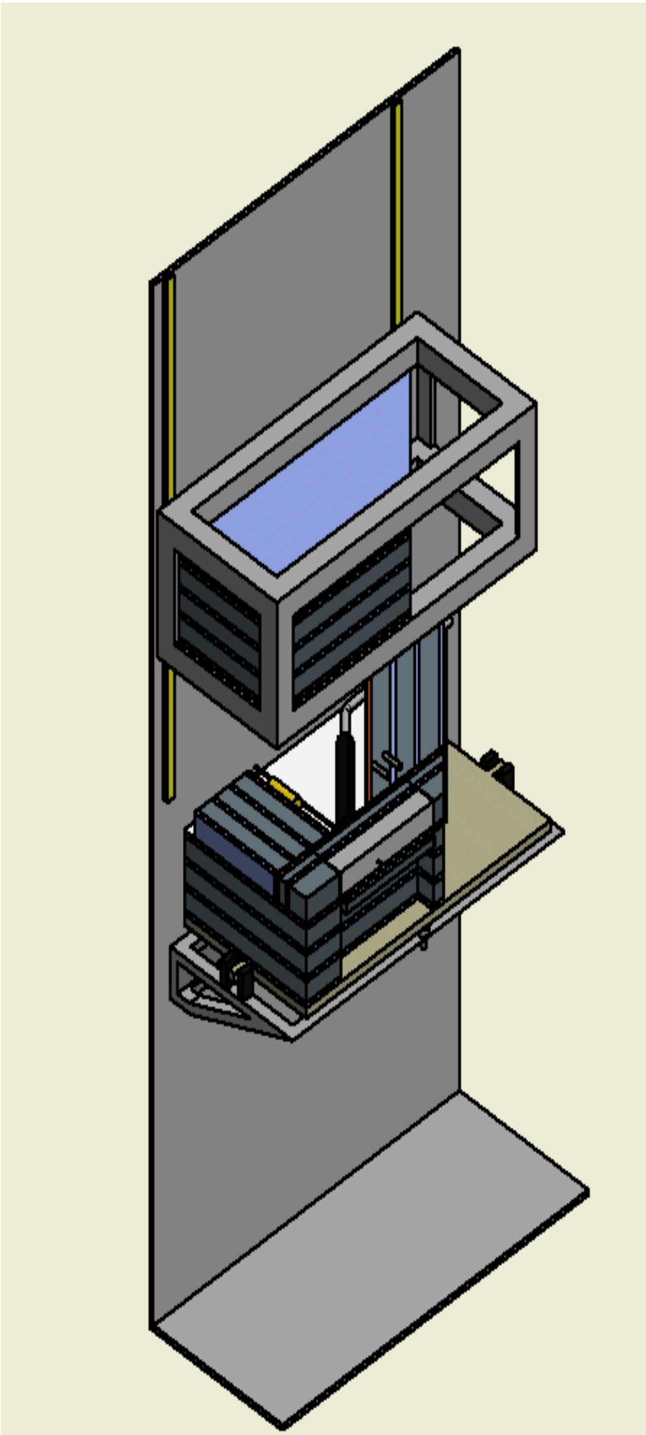
Gross adjustment to 5mm





Low housing is placed on the Base plate to within ~5 mm

Collimator has fine adjustment over 1 cm in all directions

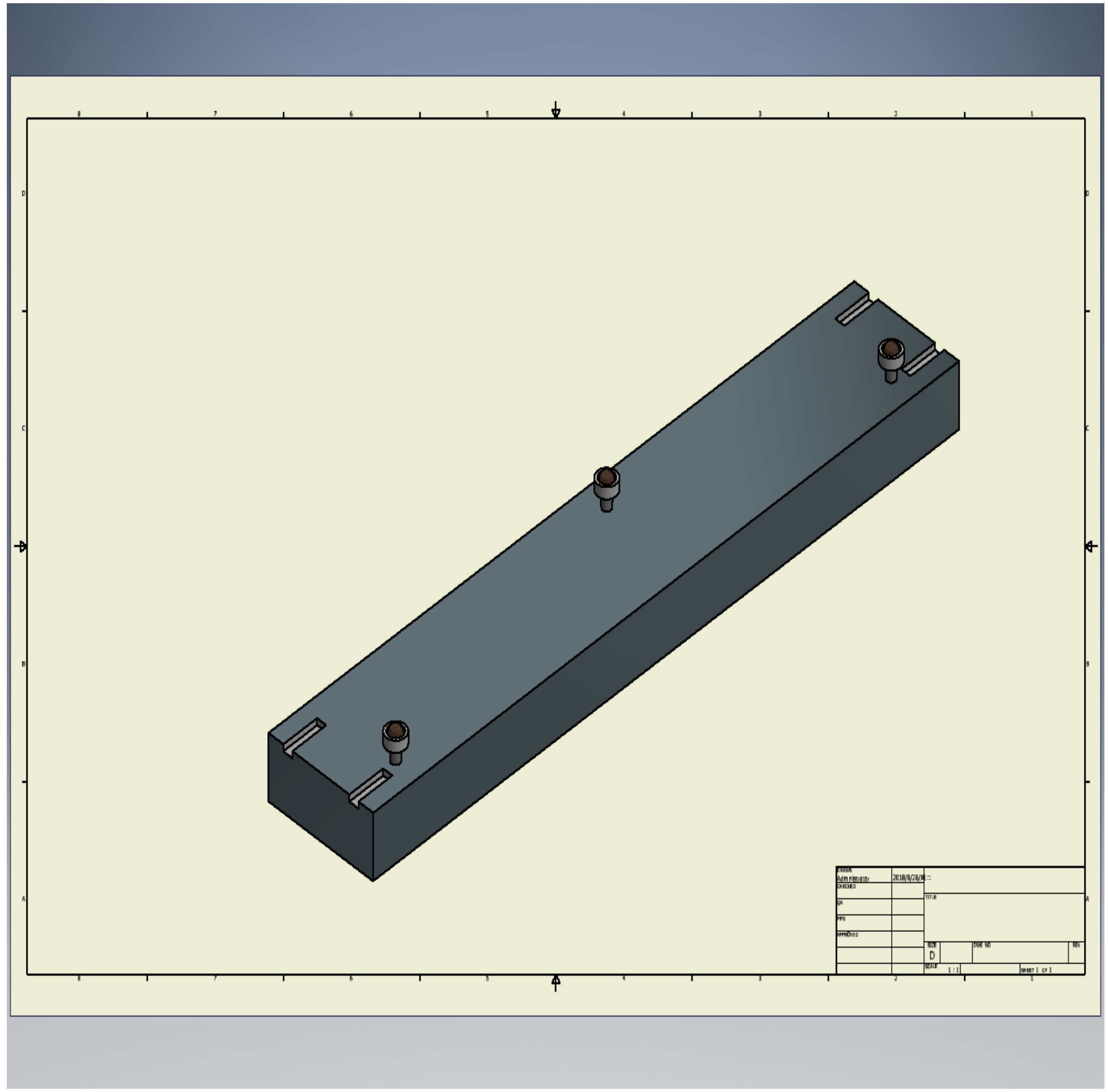


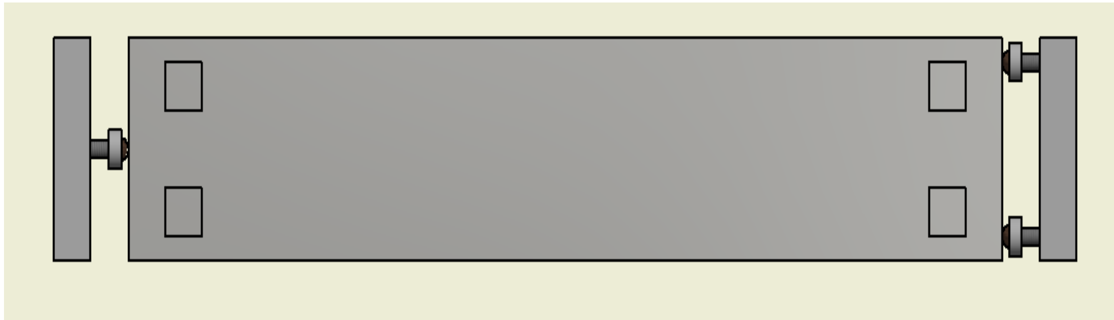
The STM Detector housing will be anchored to the floor. The floor is a large slab that serves as a reference frame for the entire experiment

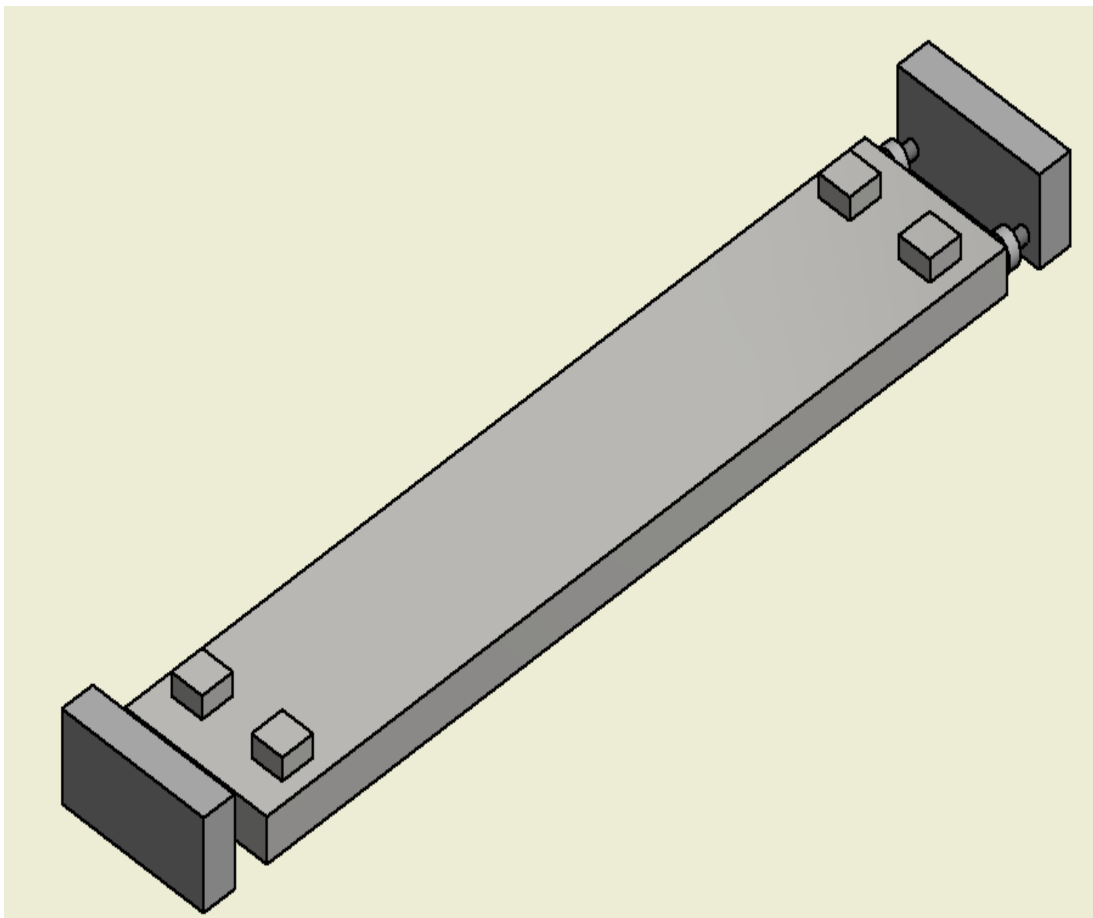
Collimator base Plate

3 point adjustment

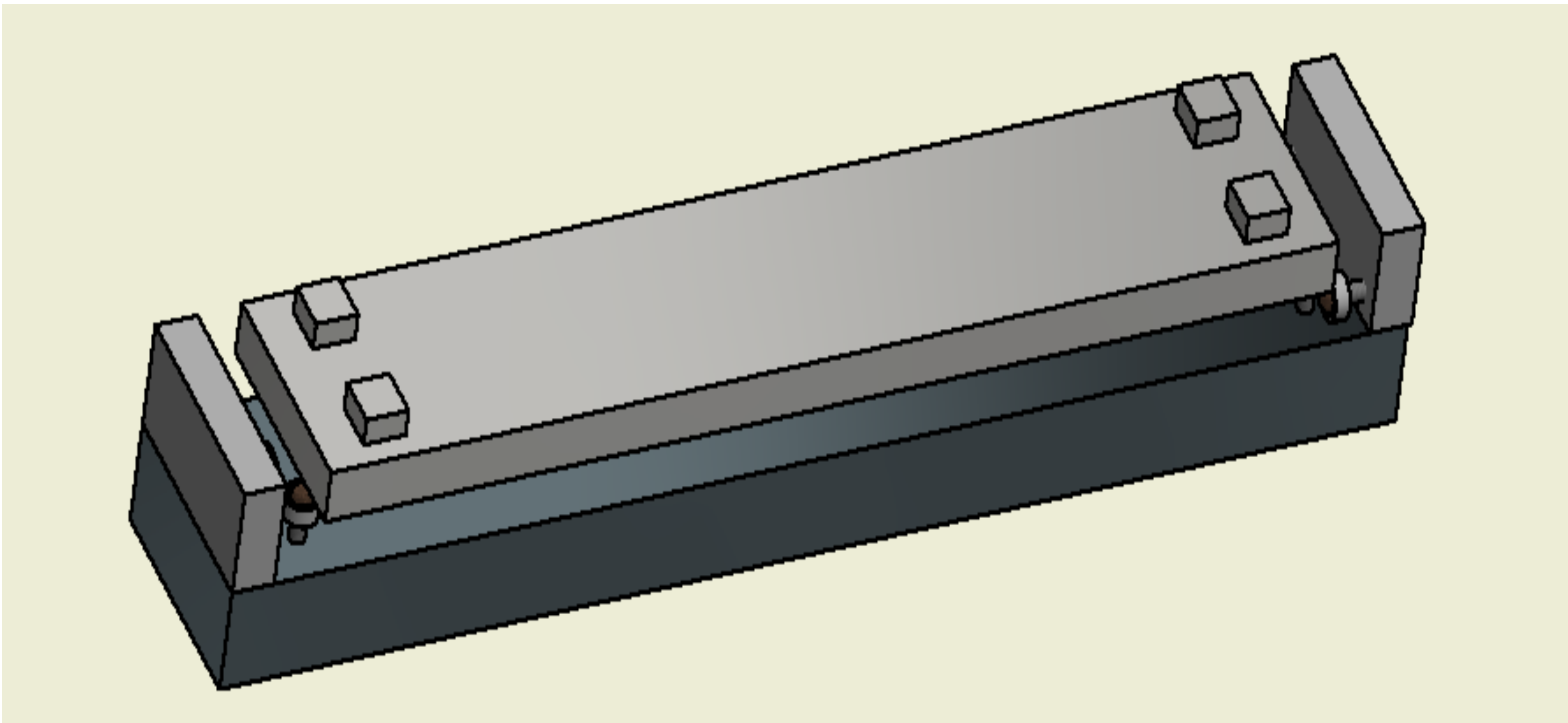
Allows
(1) Up down motion
(2) Tilt forward backward
(3) Tilt left right



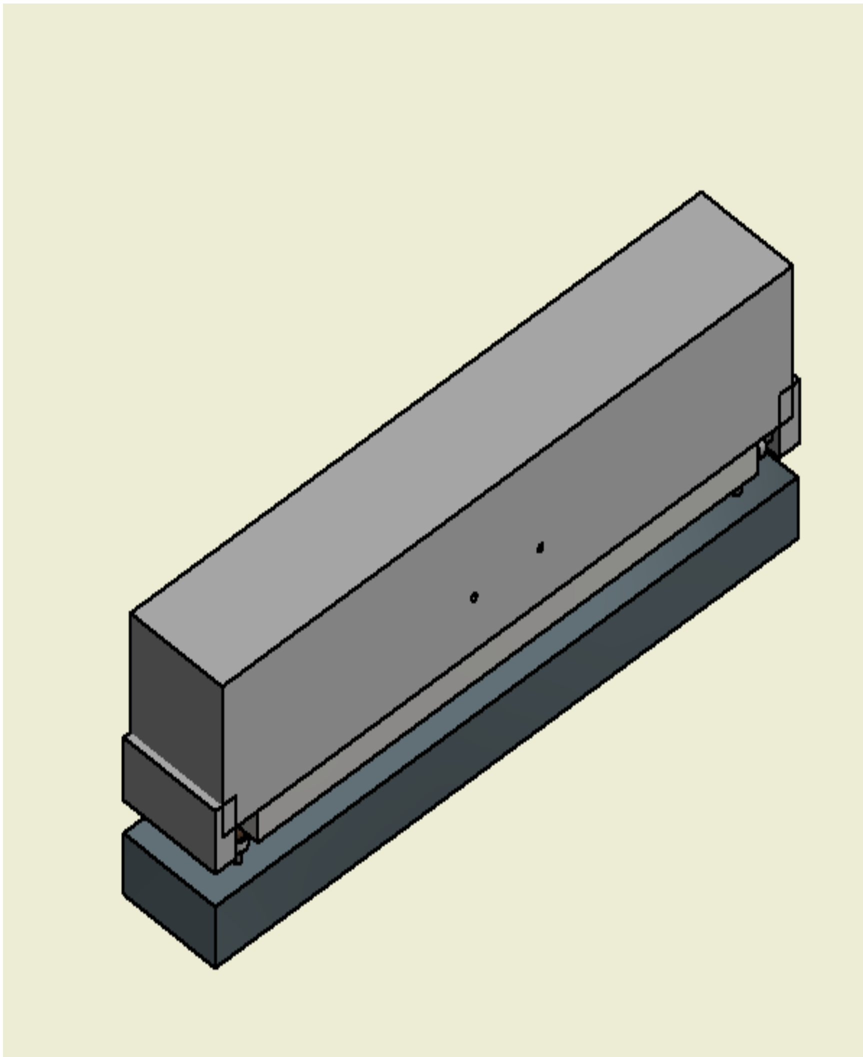




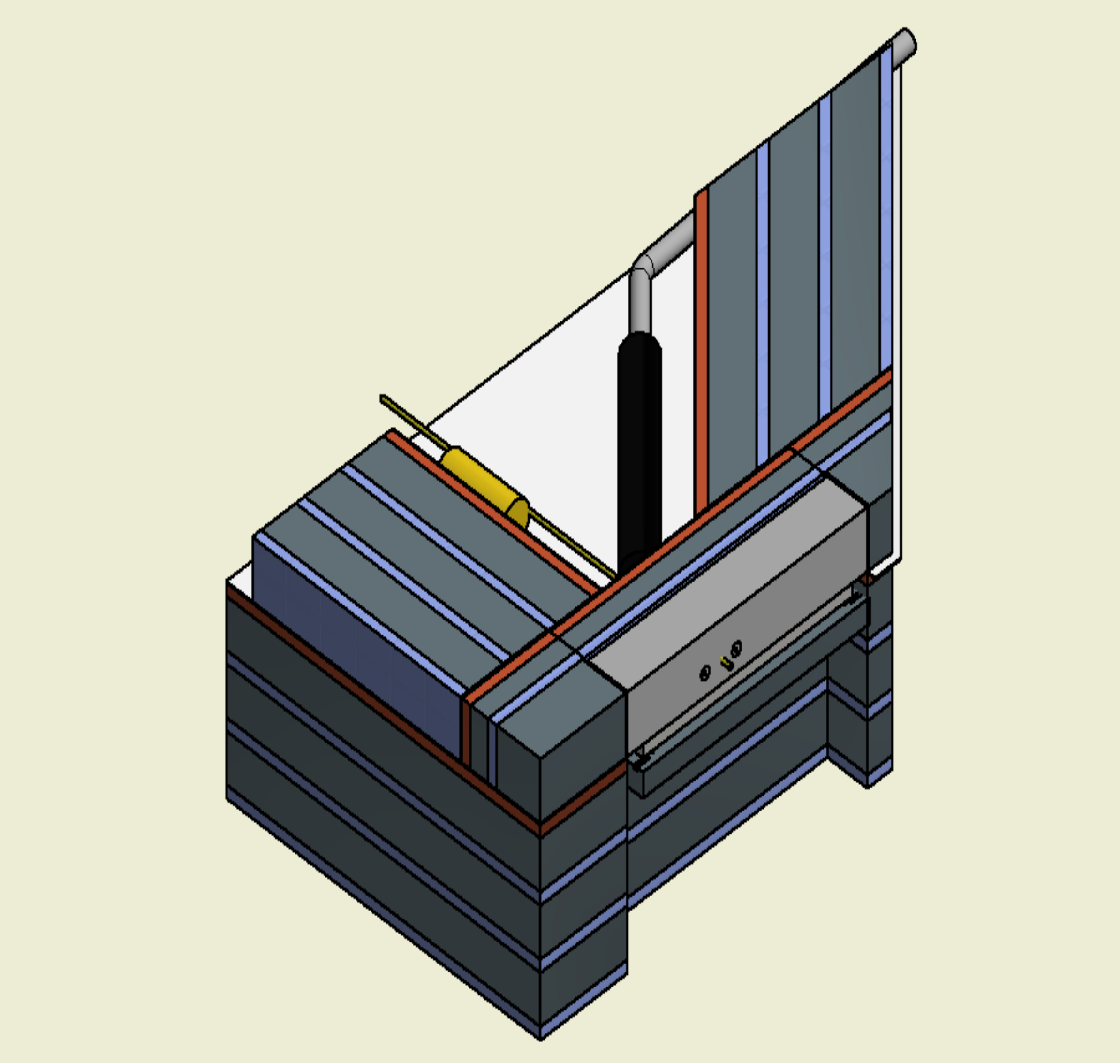
Collimator Base Plates



Collimator base plates have two orthogonal 3-point adjustments
Range of adjustment 1 cm



Tungsten Collimator captured on adjustable base plate



Collimator in place after alignment.

Shielding is attached after alignment.

Supporting and Lifting

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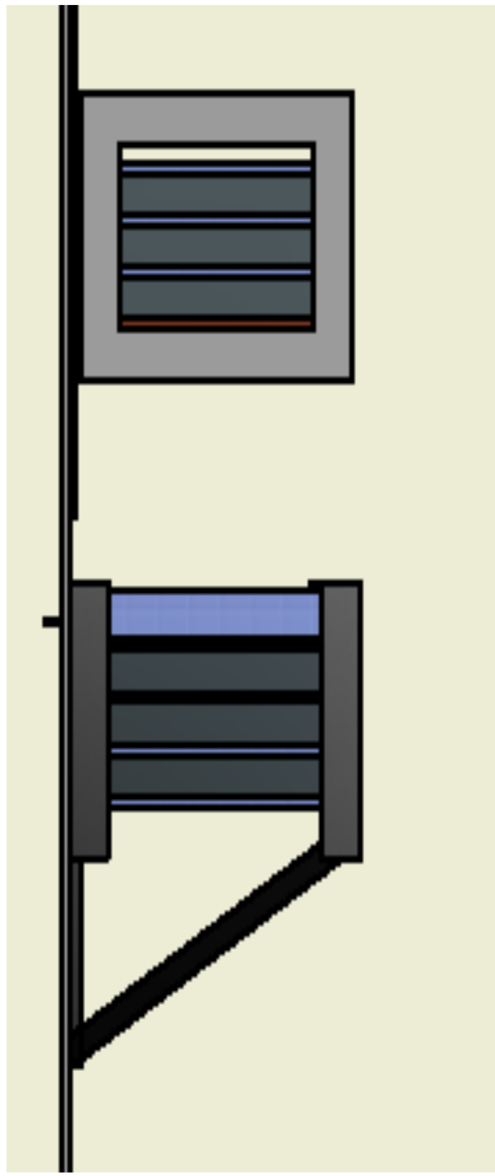
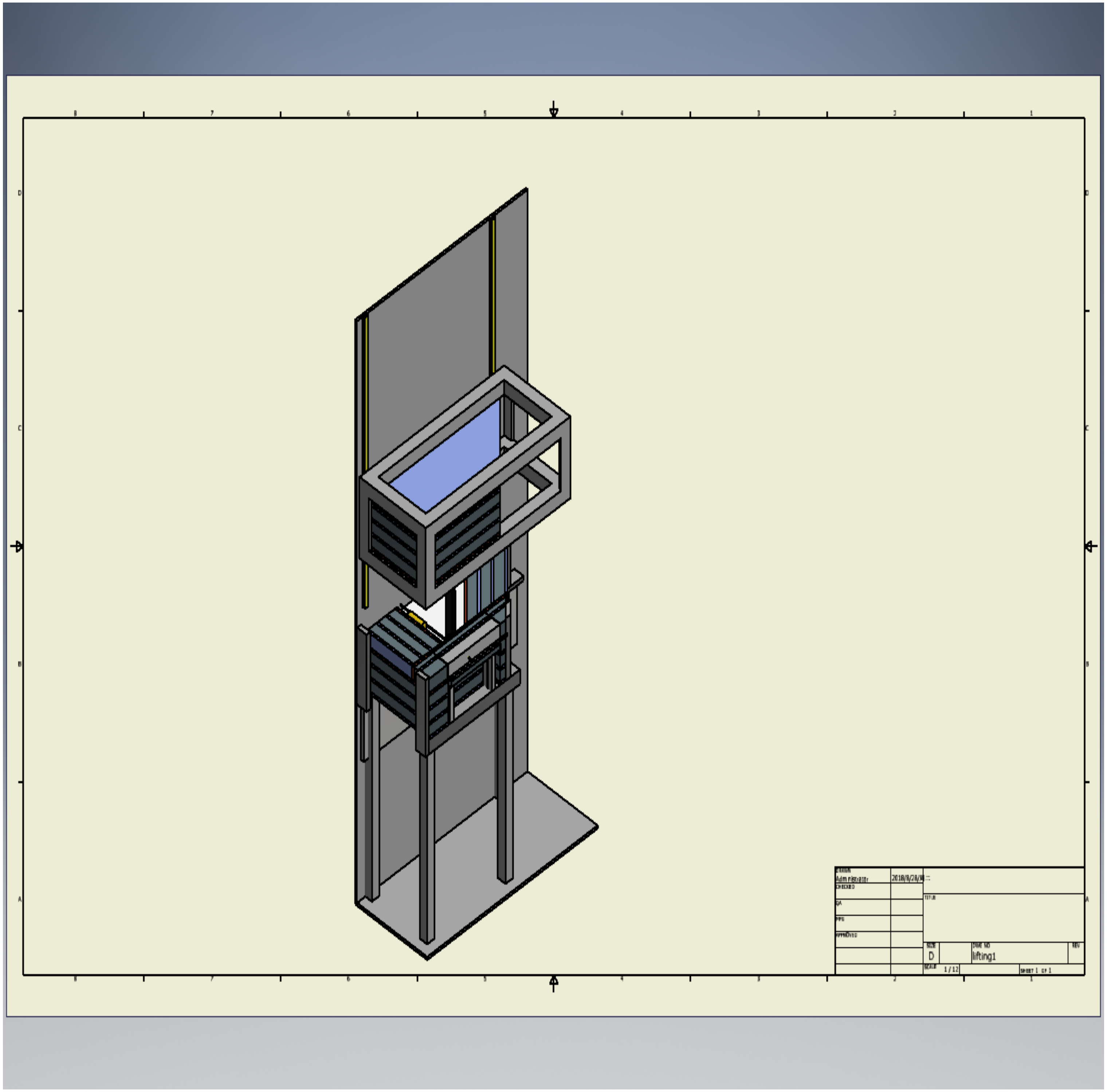
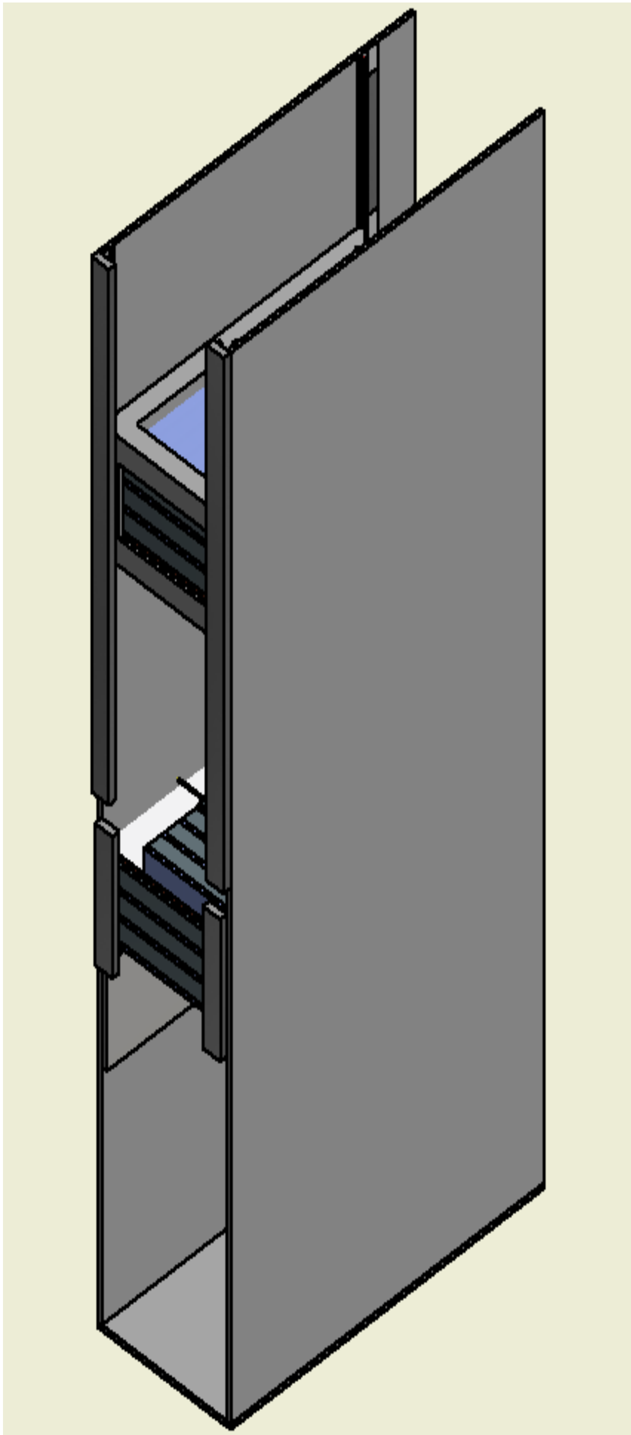
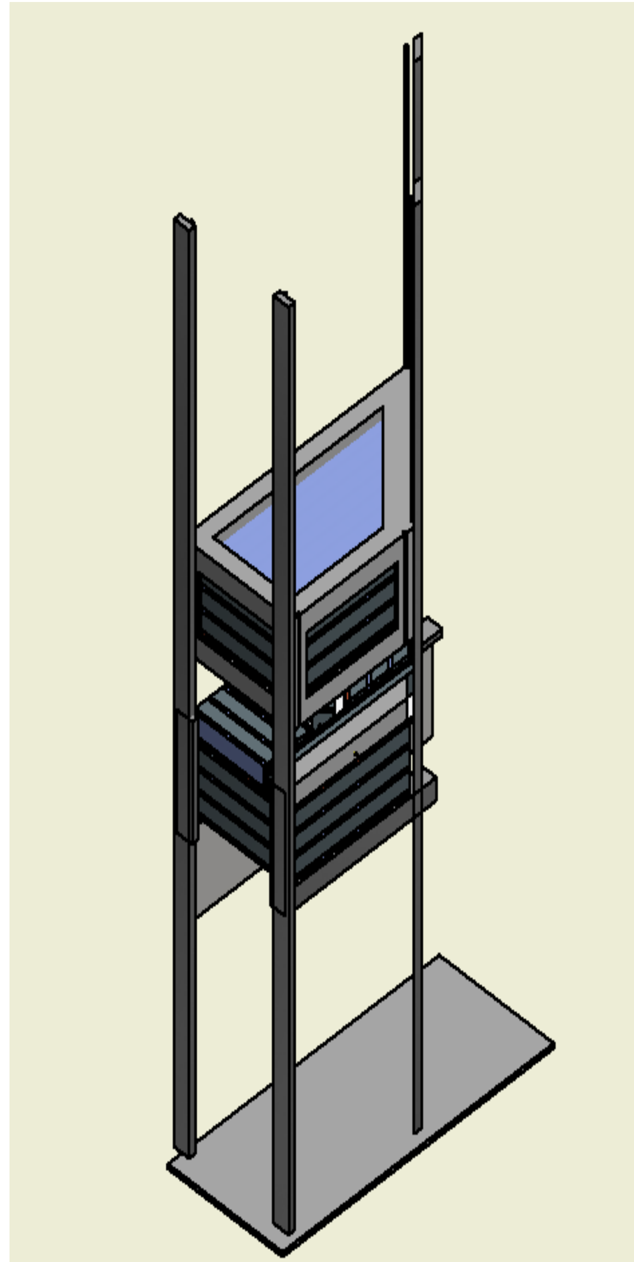



CHECKED
QA
MFG
APPROVED
TITLE
SIZE
D
DWG NO
lifting1
REV
SCALE 1 / 12
SHEET 1 OF 1

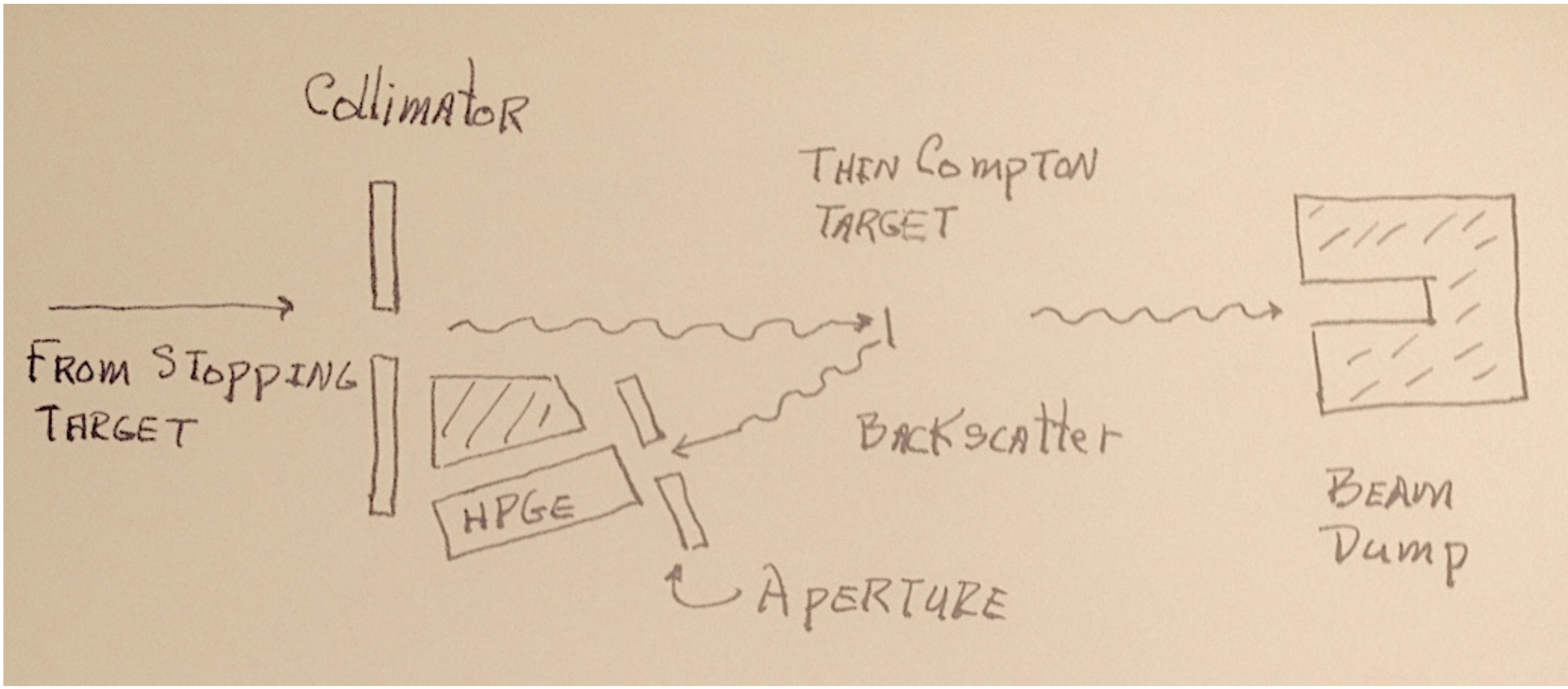
Housing Properites

- The weight
- 3 layers of lead and Polyethylene:
- Total : 11t (10857.68 kg)   upper part: 4.7t (4653.214 kg)
- 2 layers of lead and Polyethylene:
- Total : 6 t (6045.627 kg)   upper part: 2.4t (2411.839 kg)

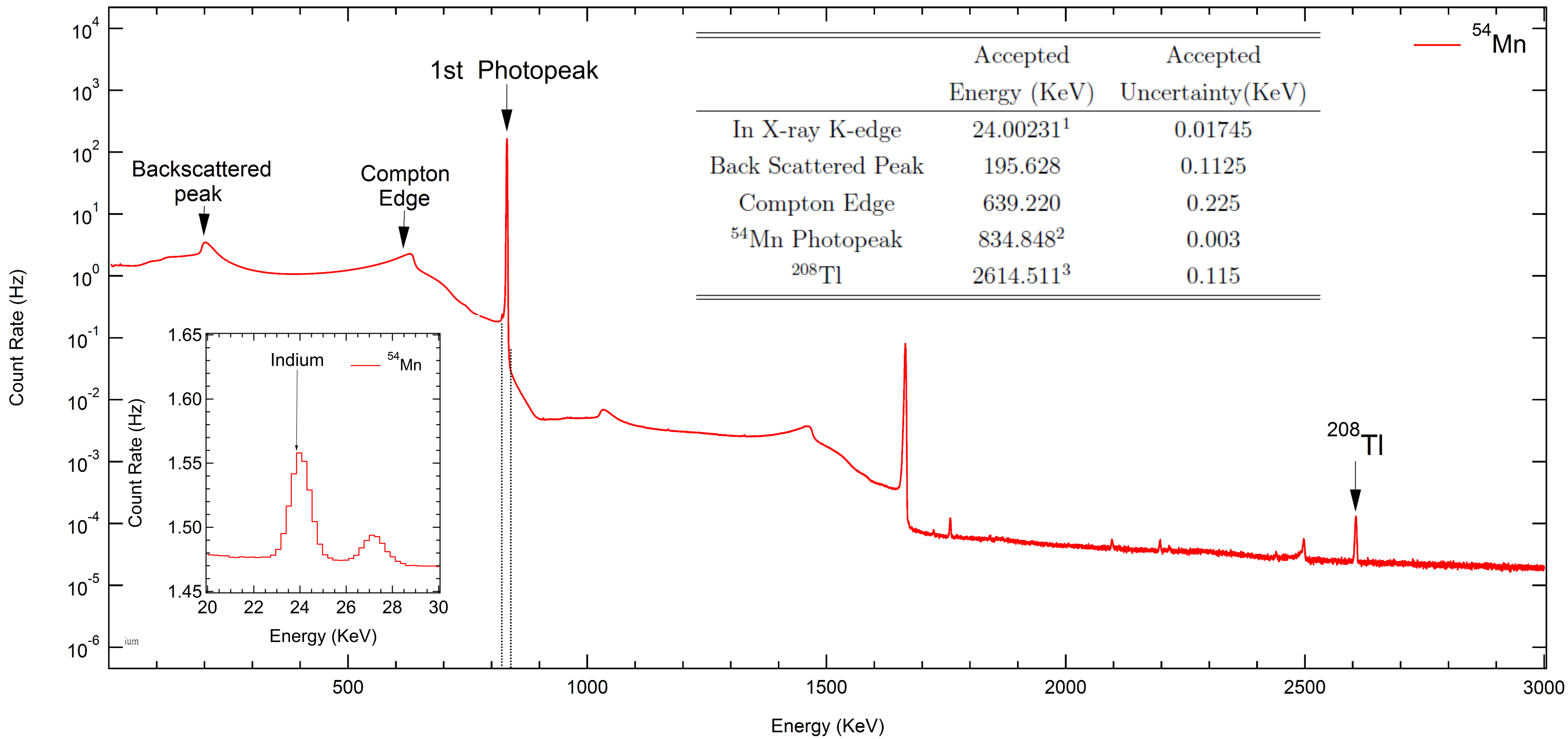
What needs to be done?

- Purchase LaBr3
- Prepare base suitable for Mu2e and Mu2e II
- Continue Design Concept
  - Group Review
  - Safety Review
- If Suitable Start Engineering Design

Mu2e II
Backscatter Spectrometer



^{54}Mn Source Spectrum Energy Calibration



	Accepted Energy (KeV)	Accepted Uncertainty(KeV)
In X-ray K-edge	24.00231[1]	0.01745
Back Scattered Peak	195.628	0.1125
Compton Edge	639.220	0.225
^{54}Mn Photopeak	834.848[2]	0.003
^{208}Tl	2614.511[3]	0.115

5 lines (Indium, Two Compton lines, ^{54}Mn, ^{208}Tl for source spectrum calibration

Theory of Compton Peak

- In Compton scattering, the gamma photon interacts with free or bound electrons of the target and gets scattered with less energy. The ***Compton Shift*** in wavelength at any angle θ is given by,

$$\lambda' - \lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

- The Compton Shift in the energy of the photon is given by

$$\frac{1}{E_{\gamma'}} - \frac{1}{E_{\gamma}} = \frac{1}{m_0 c^2}(1 - \cos\theta)$$

- It can be rewritten to

$$E_{\gamma'} = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{m_0 c^2}(1 - \cos\theta)}$$

- As the incident photons are scattered at a different angle, the Compton scattered electron have continuum distribution from zero to maximum energy

Theory of Compton Peak

- The Compton shift in energy for a head-on collision E_b (θ=180), the minimum photon energy, is given by

$$\frac{1}{E_b} - \frac{1}{E_\gamma} = \frac{2}{m_0 c^2}$$

- This energy is also known as the backscattered photon also can be rewritten by

$$E_b = \frac{E_\gamma}{1 + 2\frac{E_\gamma}{m_0 c^2}}$$

- The Compton edge is the maximum energy of an electron from Compton scattering,

$$E_{\max} = E_\gamma - E_b = E_\gamma \left(1 - \frac{1}{1 + 2\frac{E_\gamma}{m_0 c^2}} \right)$$

- Based on the ^{54}Mn Photoepeak energy **834.848 KeV**, the theoretical backscattered energy is at **195.629 KeV.** The theoretical Compton edge is at **639.220 KeV.**

Advantage 1

- The problem with viewing the target directly is high average energy of the Gamma Rays. Up to 75 MeV
- Backscatter- High Energy Deposition is greatly reduced $E_{back} = \frac{E_\gamma}{1 + 2\frac{E_\gamma}{m_e}} \quad \frac{Limit}{E_\gamma \to \text{large}} \sim \frac{m_e}{2}$

75 MeV Gamma Rays Deposit only $\frac{m_e}{2}$

Advantage 2

The interaction cross section

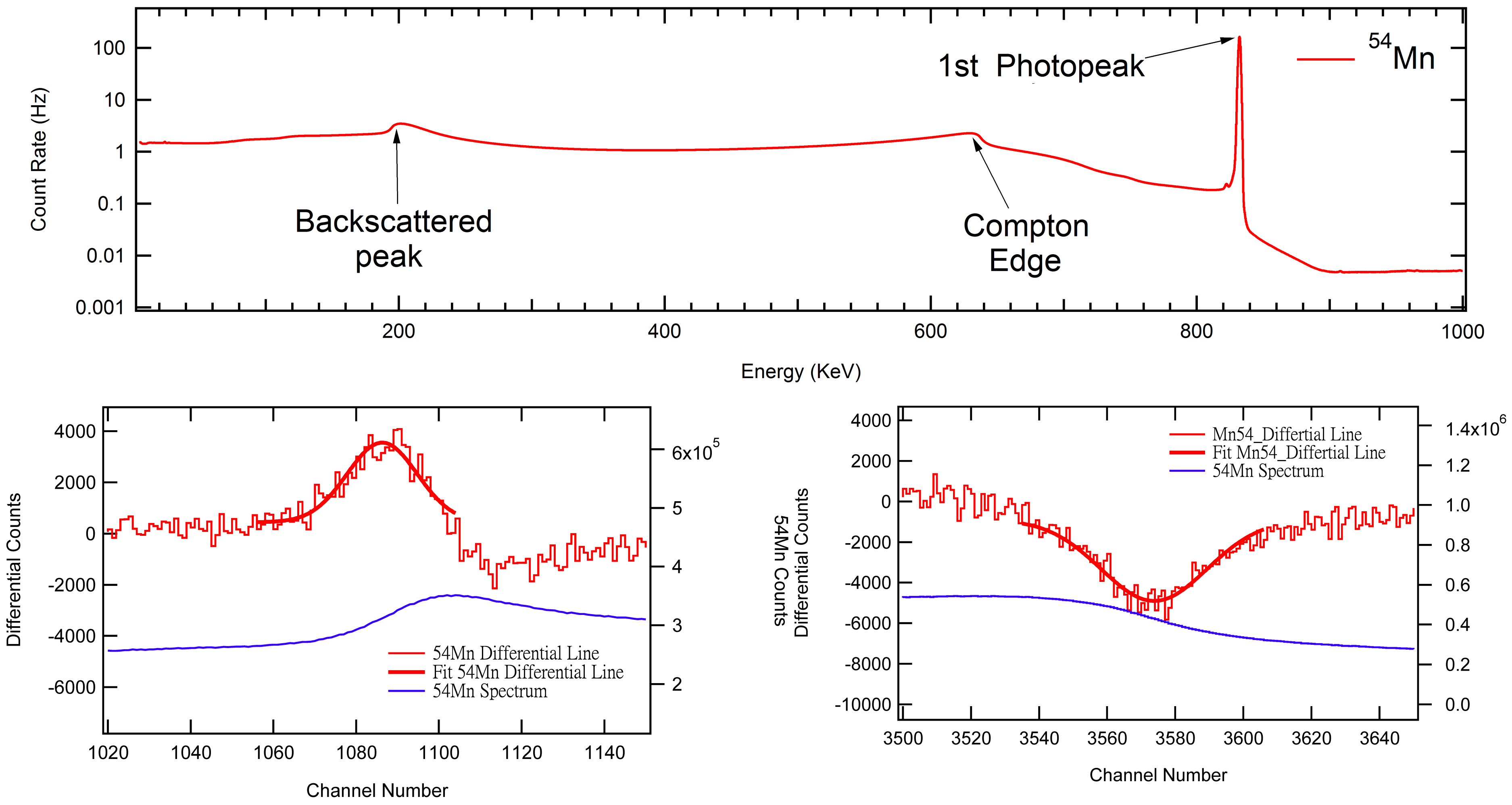
$$\sigma = \pi r_e^2 \frac{m_e}{E_\gamma}\left[\log\frac{2E_\gamma}{m_e} + \frac{1}{2}\right]$$

Drops as a function of Gamma Ray Energy ~ $\frac{m_e}{E_\gamma}$

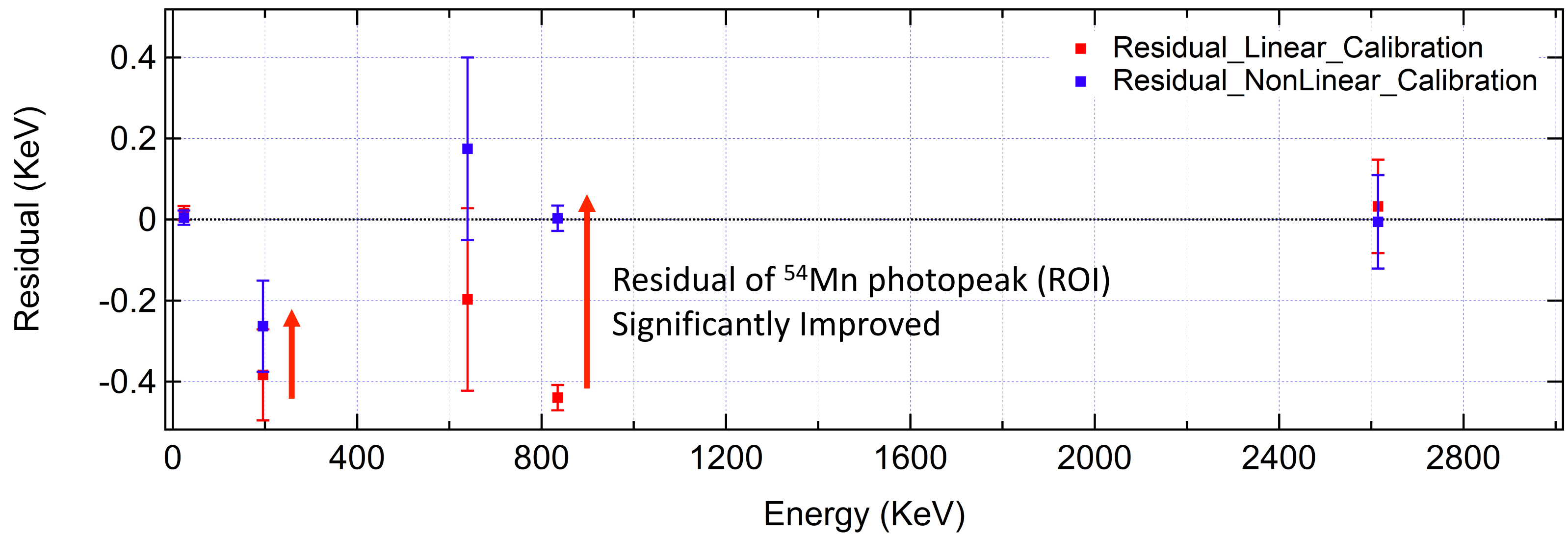
75 MeV Gamma Rays produce 1/150 those at 500 keV!
10 MeV Gamma Rays produce 1/20 those at 500 keV!

Where as when viewing the Stopping Target directly these will deposit some amount of energy in the thick detector.

Compton Differential Peaks for Calibration



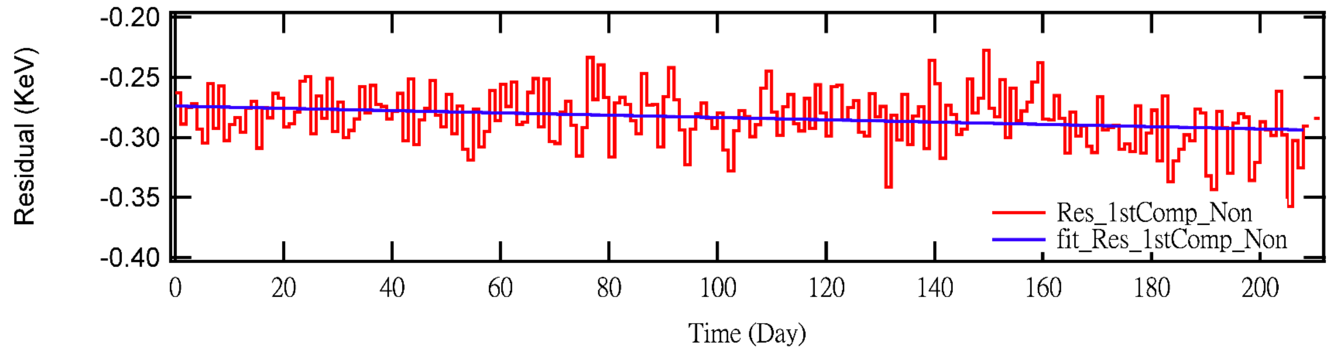
Improved ^{54}Mn Source Spectrum Nonlinear Energy Calibration



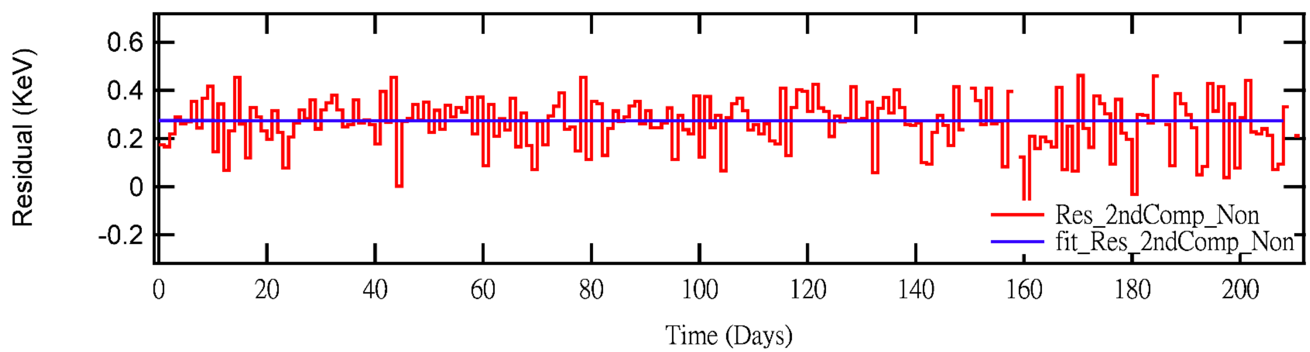
^{54}Mn Source Spectral				
Type of Calibration	a_0 (KeV)	a_1 (KeV/No.)	a_2 (KeV/No.^{2})	χ^2_{Deg}
Linear	0.0691±6.5136E-04	0.2257±9.10142E-11	N/A	31.43
Non-linear	0.0068±0.0175	0.2258±1.4859E-5	-1.5129E-08±1.6833E-9	3.07

Chi-Squared/deg Significantly drop 1/10

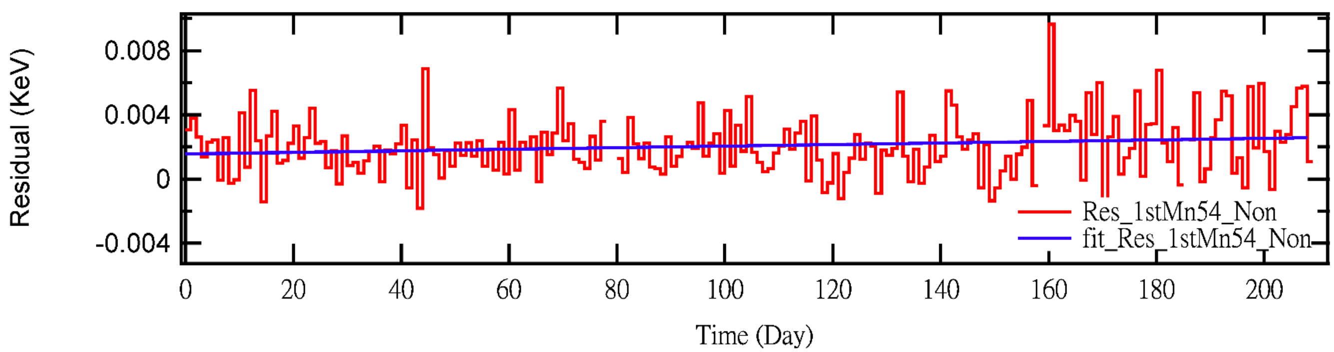
Daily Residual after Calibration



Back Scattering Peak

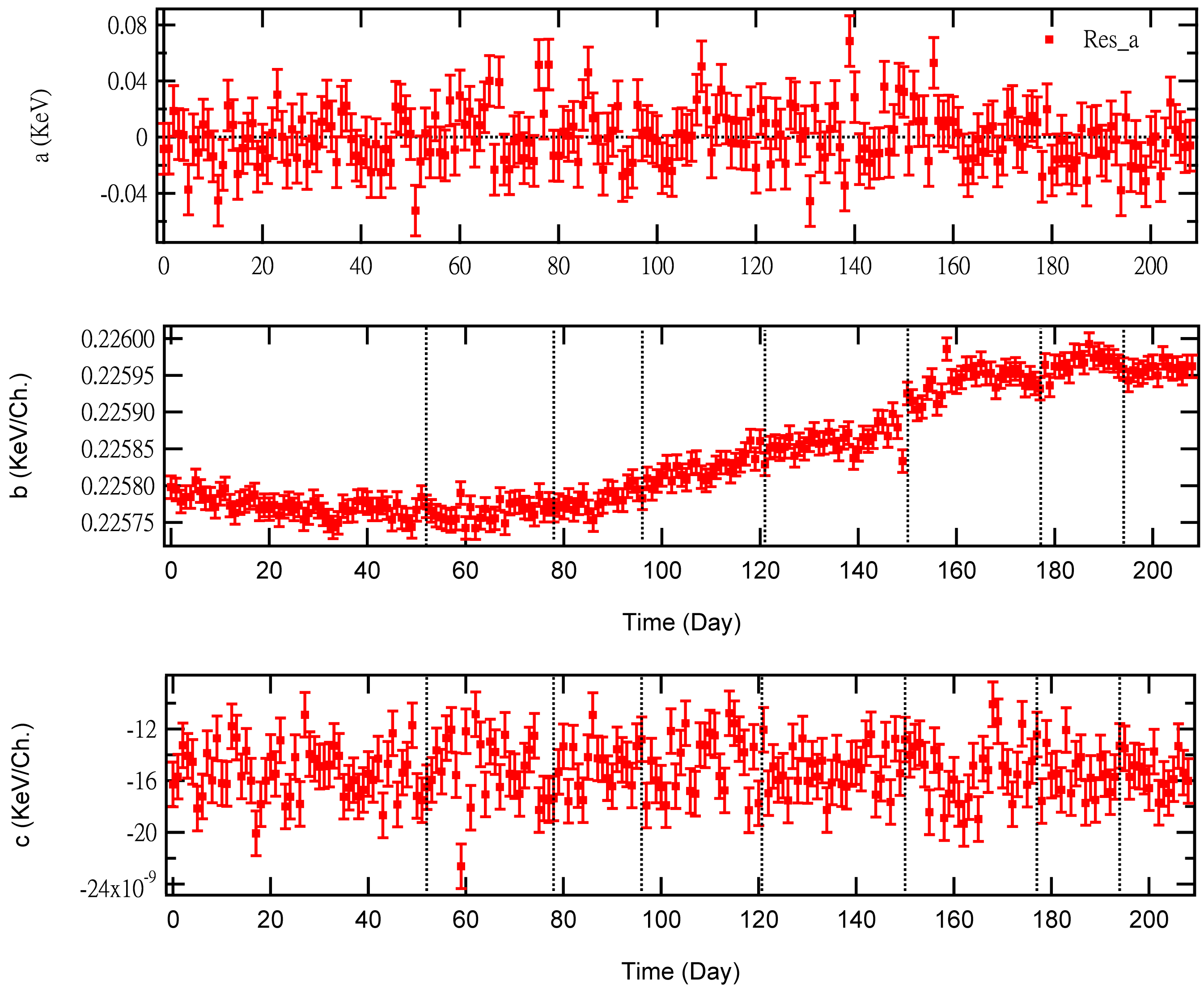


Compton Peak

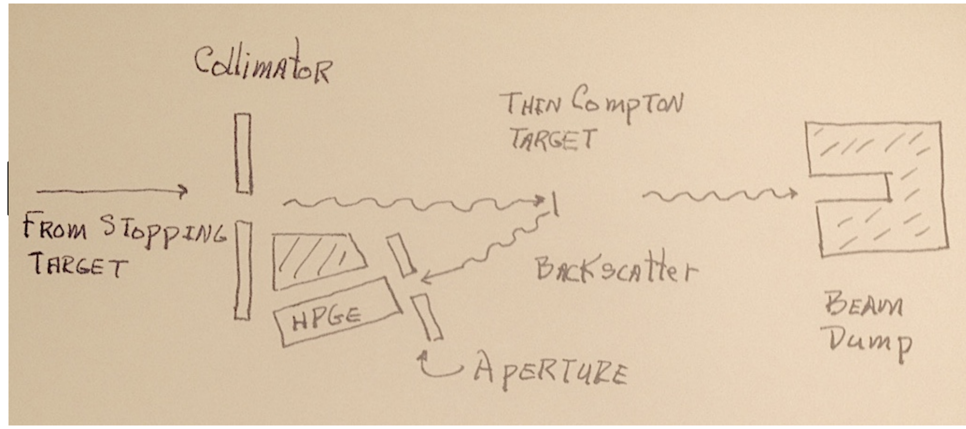


54Mn Photopeak

Daily Calibration Coefficient of HPGe Detector



Adva

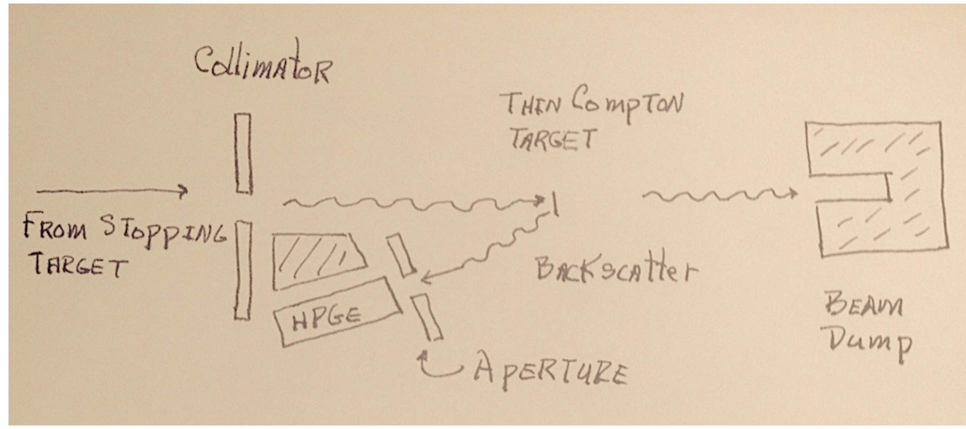


Scale of compression can be tuned by selecting the target viewing angle

$$\sigma(E_{scatter})dE_{scatter} = \pi r_e^2 \frac{m_e dE_{scatter}}{E_\gamma E_{scatter}}(1+\frac{E_{scatter}}{E_\gamma})$$

Cross section still drops off strongly

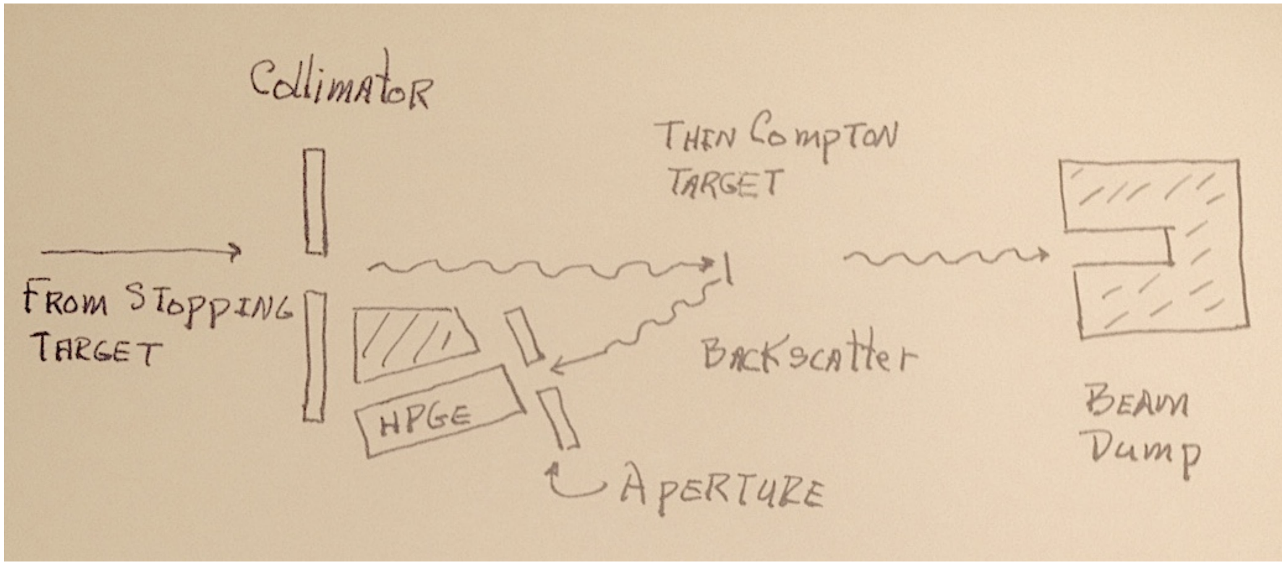
Advantage 4



Detector Rate is Selectable by Target Thickness and Width

Advantage 5

Line width is related to the Detector Aperture setting



Advantage 6

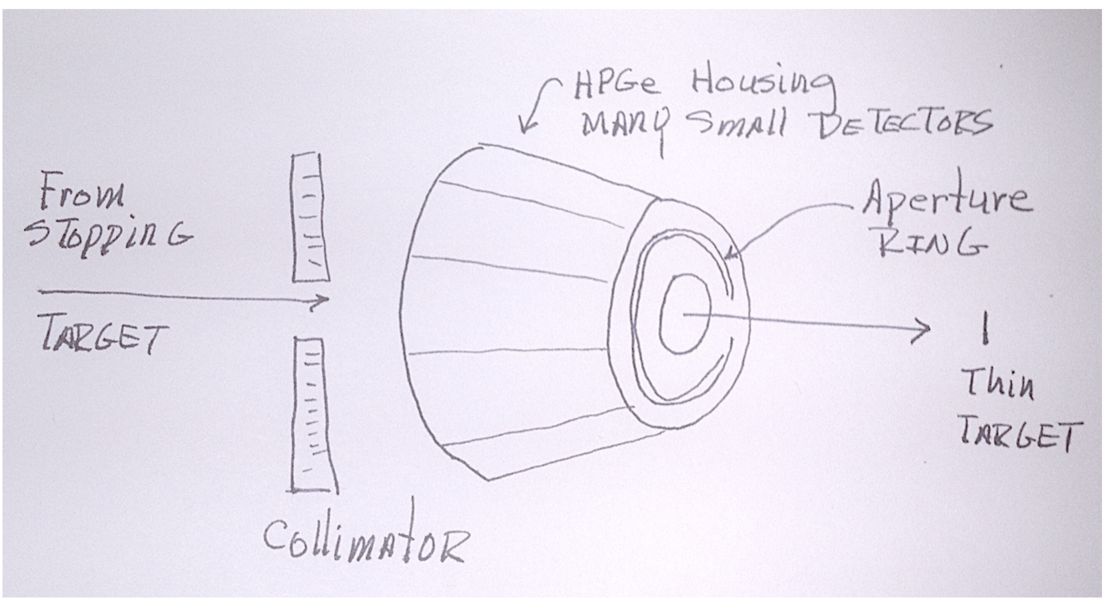
Much Less Radiation Damage because Average Energy Deposition is Greatly Reduced

Advantage 7

The differential Spectrum gives accurate line Energy

What Needs to be Done?

- Design and model a system to see if performance is acceptable: A single large commercial Detector
- Take advantage of the low energies by using many small HPGe detectors and still achieve good acceptance and energy resolution



Look Directly At the Stopping Target be Capable of 1Mcps

High-Purity Germanium Spectroscopy at Rates in the Excess of 1Million cps.

Brent A. VanDevender et. al.,

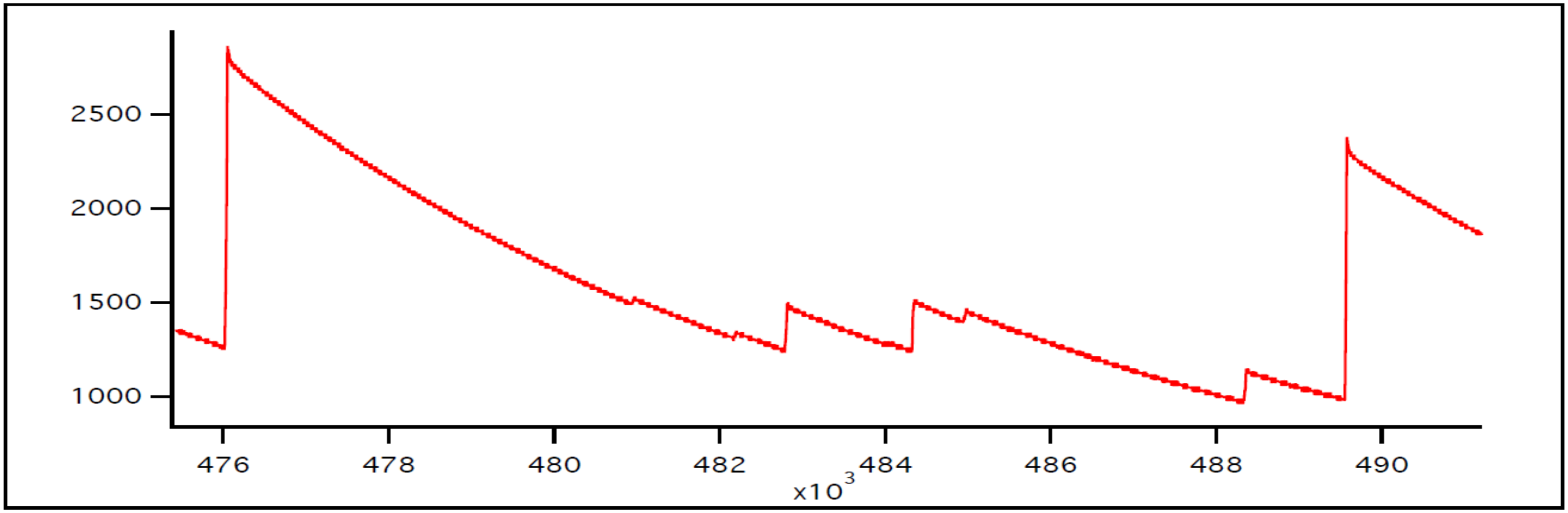
IEEE Transactions on Nuclear Science

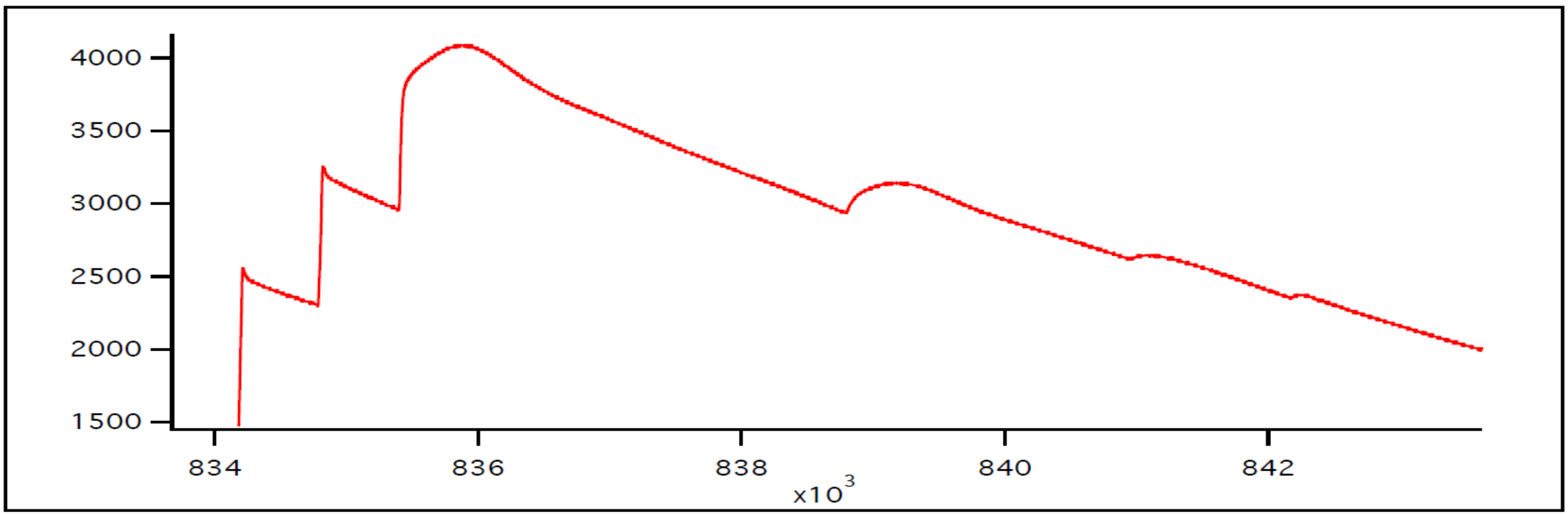
Vol. 6 No. 5 October 2014

Abstract

We report the performance of an HPGe spectrometer system adapted run at more than 1Mcps. Our system consists of a commercial semi-coaxial HPGe detector, a modified (100v) high-voltage rail, resistive-feedback, charge-sensitive preamplifier and a continuous waveform digitizer. Digitized waveforms are analyzed offline with a novel time-variant trapezoidal filter algorithm. Several time-invariant trapezoidal filters are run in parallel and the slowest one not rejected by instantaneous pileup conditions is used to measure each pulse height. We have attained FWHM energy resolution approximately 8 keV measured at 662 keV with 1.03Mcps and 39% throughput. An additional constraint on the width of the fast trigger filter removes a significant amount of rising edge pileup that passes the first pileup cut, reducing throughput to 25%. While better resolution has been reported by other authors, our throughput is an order of magnitude higher than any other reported HPGe system operated at such an event rate.

Possible problem 2: bad events in raw data





What to be done?

- Purchase amplifier with high-voltage
- DAQ capable of streaming 1M events/second
- Compute Power to keep up offline
- Develop algorithms

- Attempt inline algorithm to build spectra based on the experience offline.

Reconstruction Algorithm Studies

MWD-Moving Window De-convolution

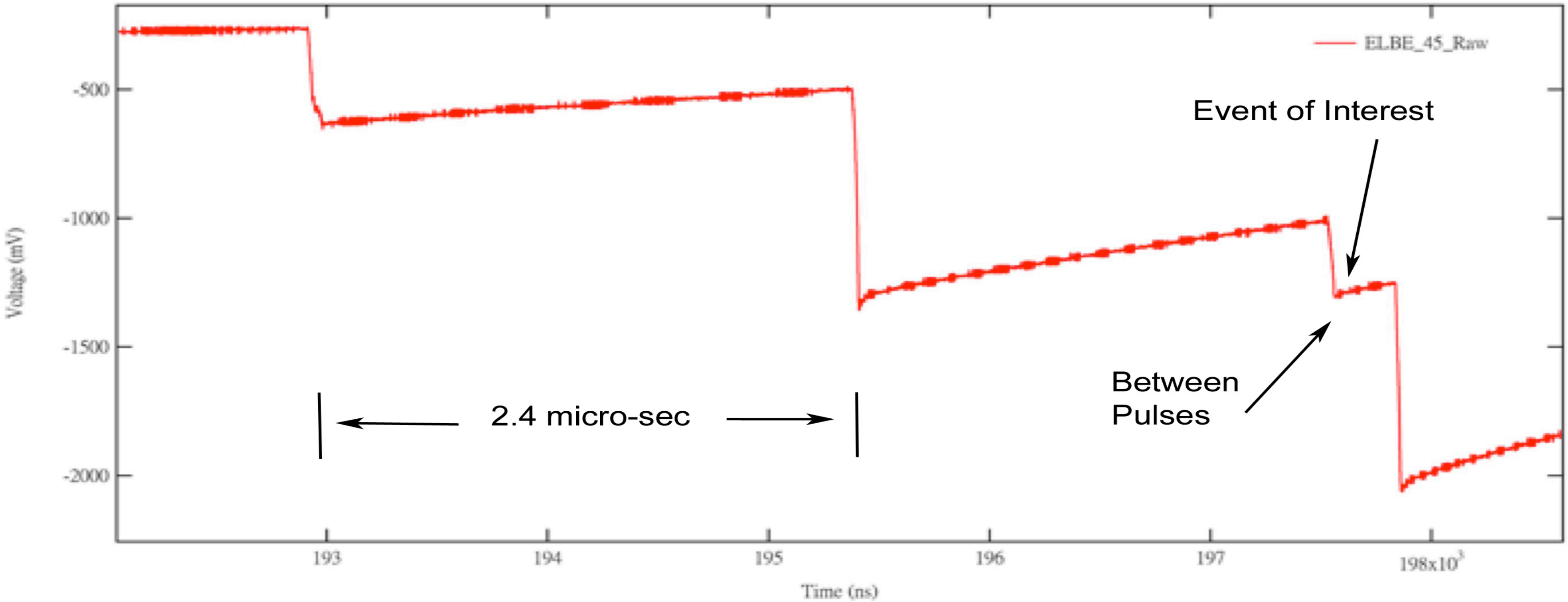
Standard Signal Reconstruction Algorithm

Can a New Approach Significantly Improve Reconstruction Efficiency?

DMA- De-convolution Moving Average

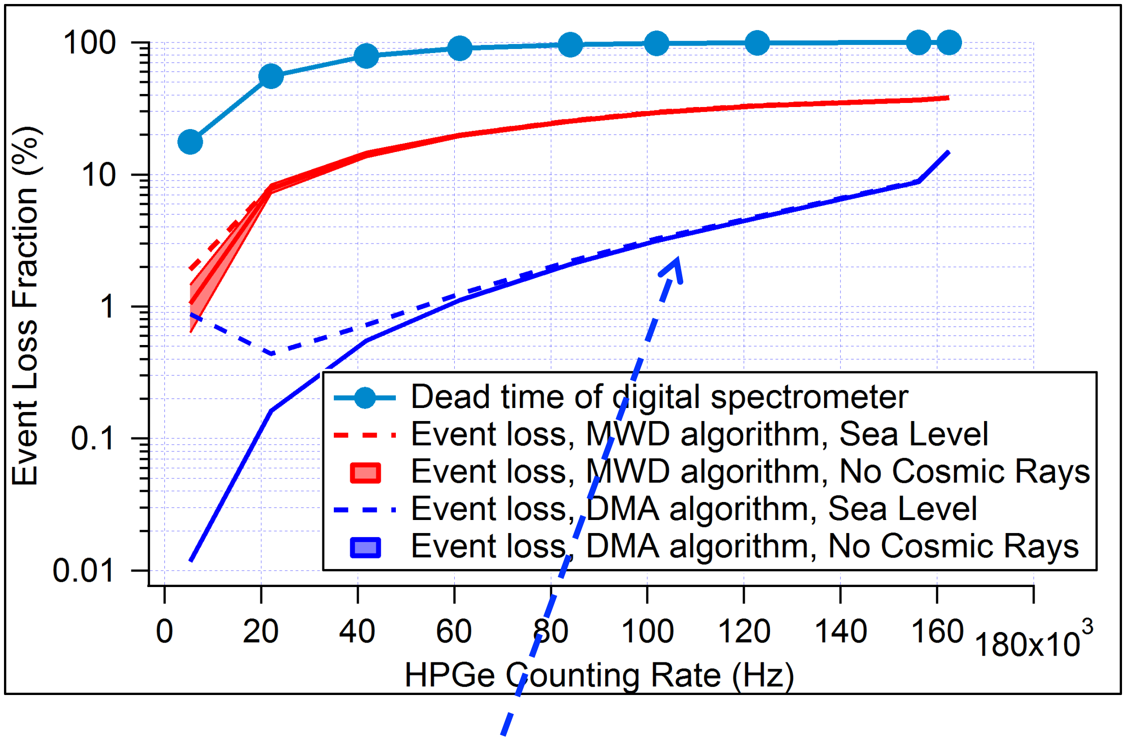
Has been shown to work well at high rates and low average energy.

Algorithm Studies Goals



Large Dynamic Range Limits "dead time" due to ADC overflow
The number of ADC bits and dynamic range yield the energy resolution
The HPGe detectors requires no events for tau~ 50-60 micro-second to return to base-line

Dead time and Event Loss Issue at Continuous Mode

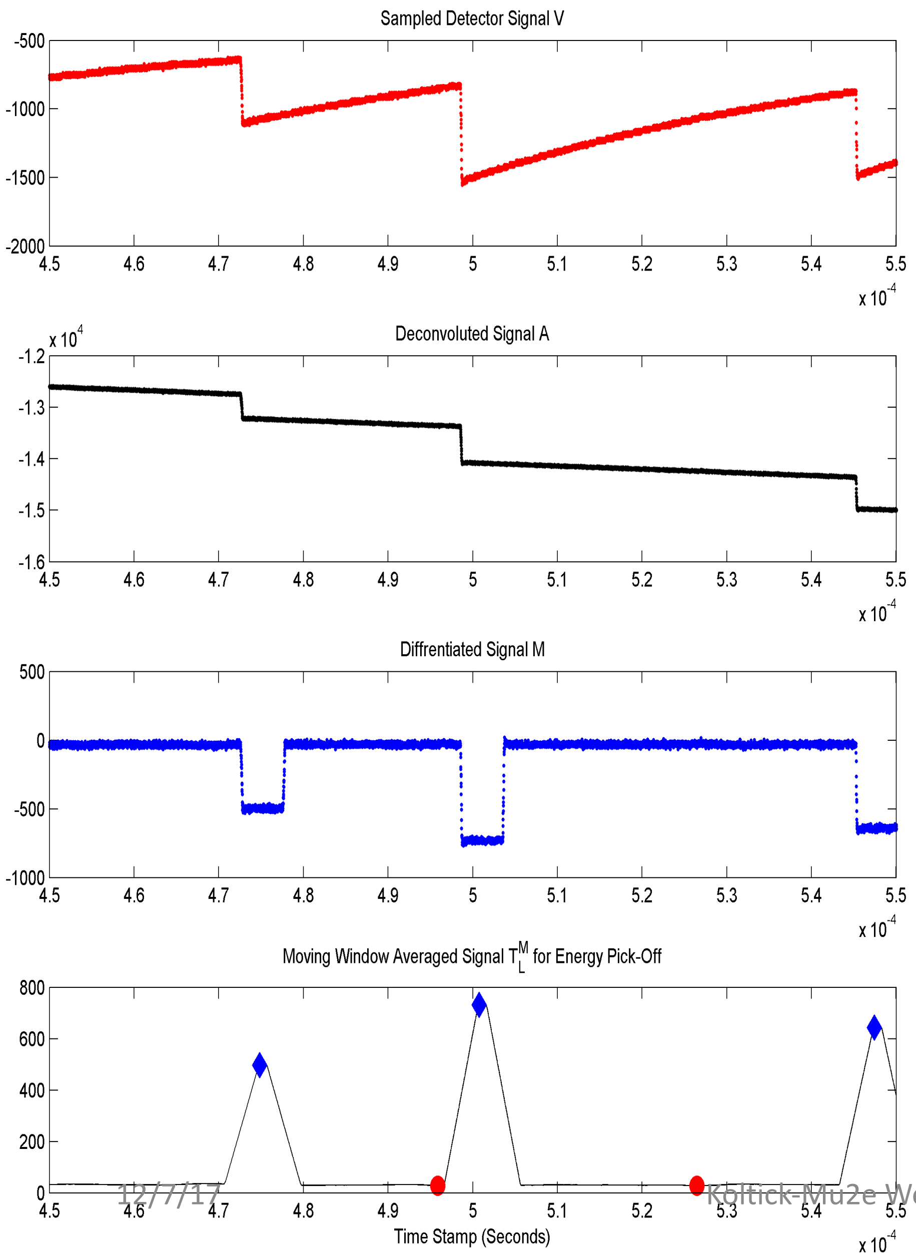


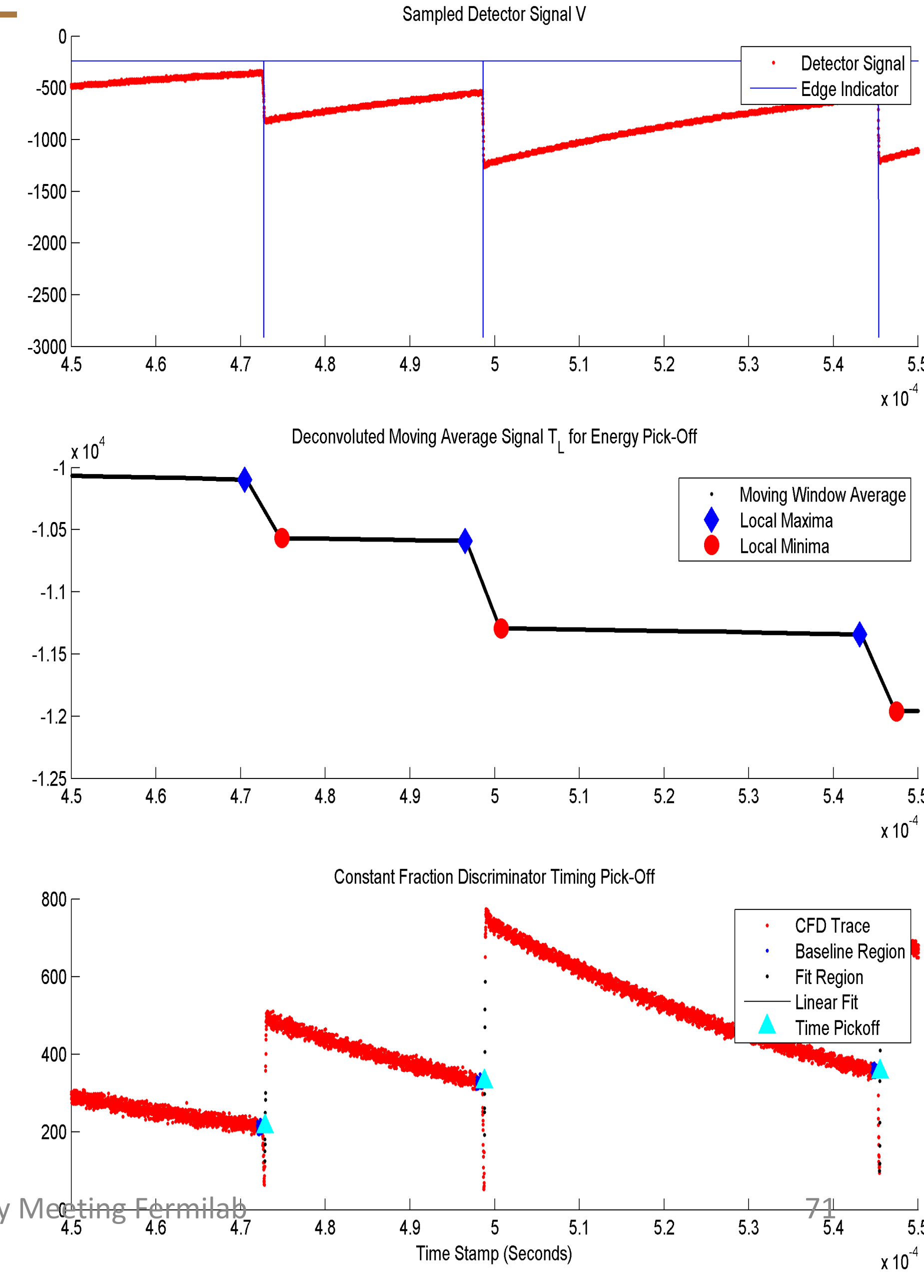
For rates ~100 kHz, the DMA algorithm is able to keep:

(1) Dynamic range overflow event loss < 5.8×10^{-3}

(2) Pile-up event loses to < 2.6×10^{-2} in both ~100% n-type and p-type HPGe detectors when working with sources.

Compare: MWD DMAB-CFD





Dead time and Event Loss Issue: MWD

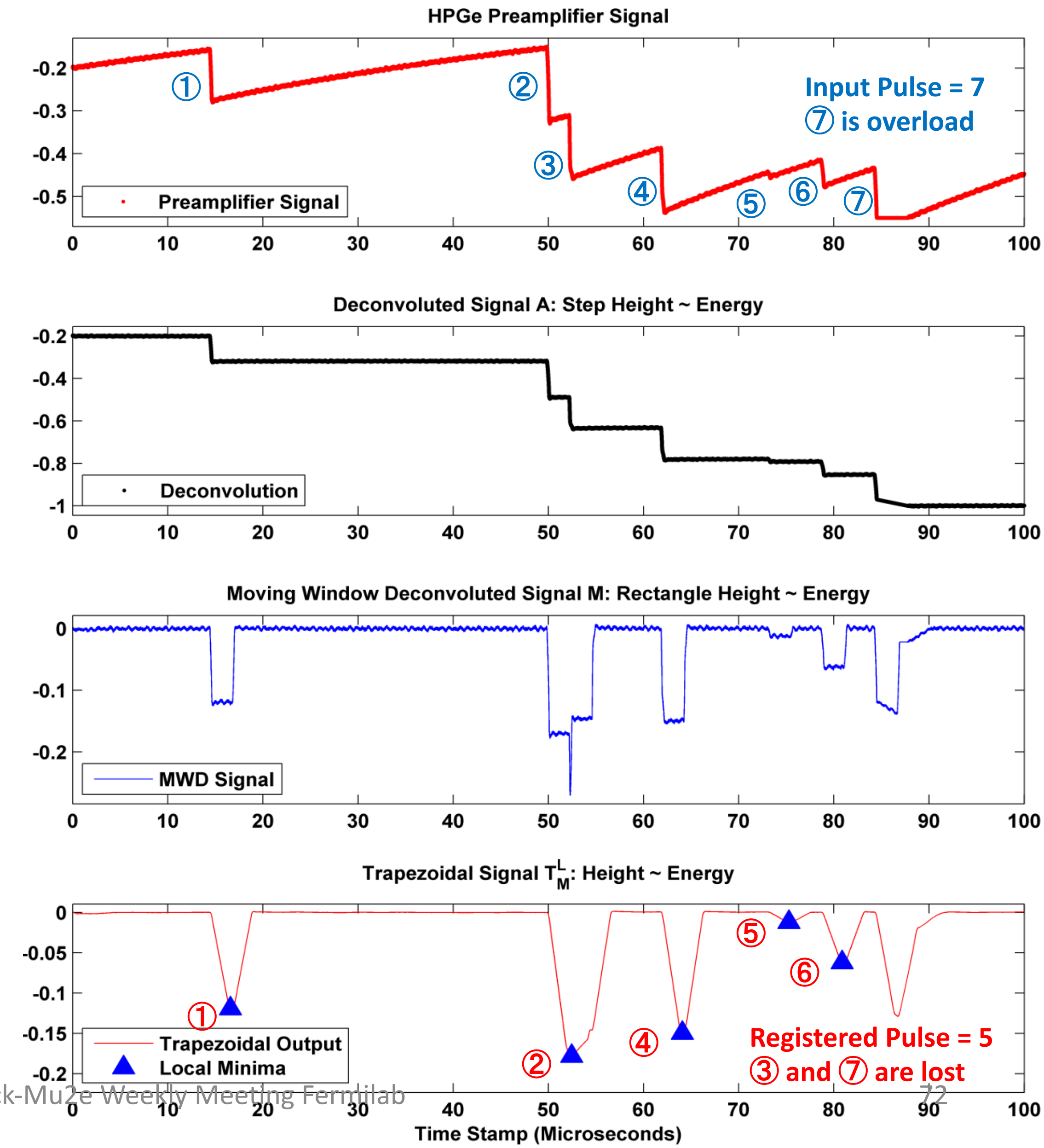
Example: **MWD**

- Electronic dynamic range overload;
- Signal processing algorithm: nearby rejection

Step 1: Deconvolution

Step 2: Differentiation

Step 3: Moving Average

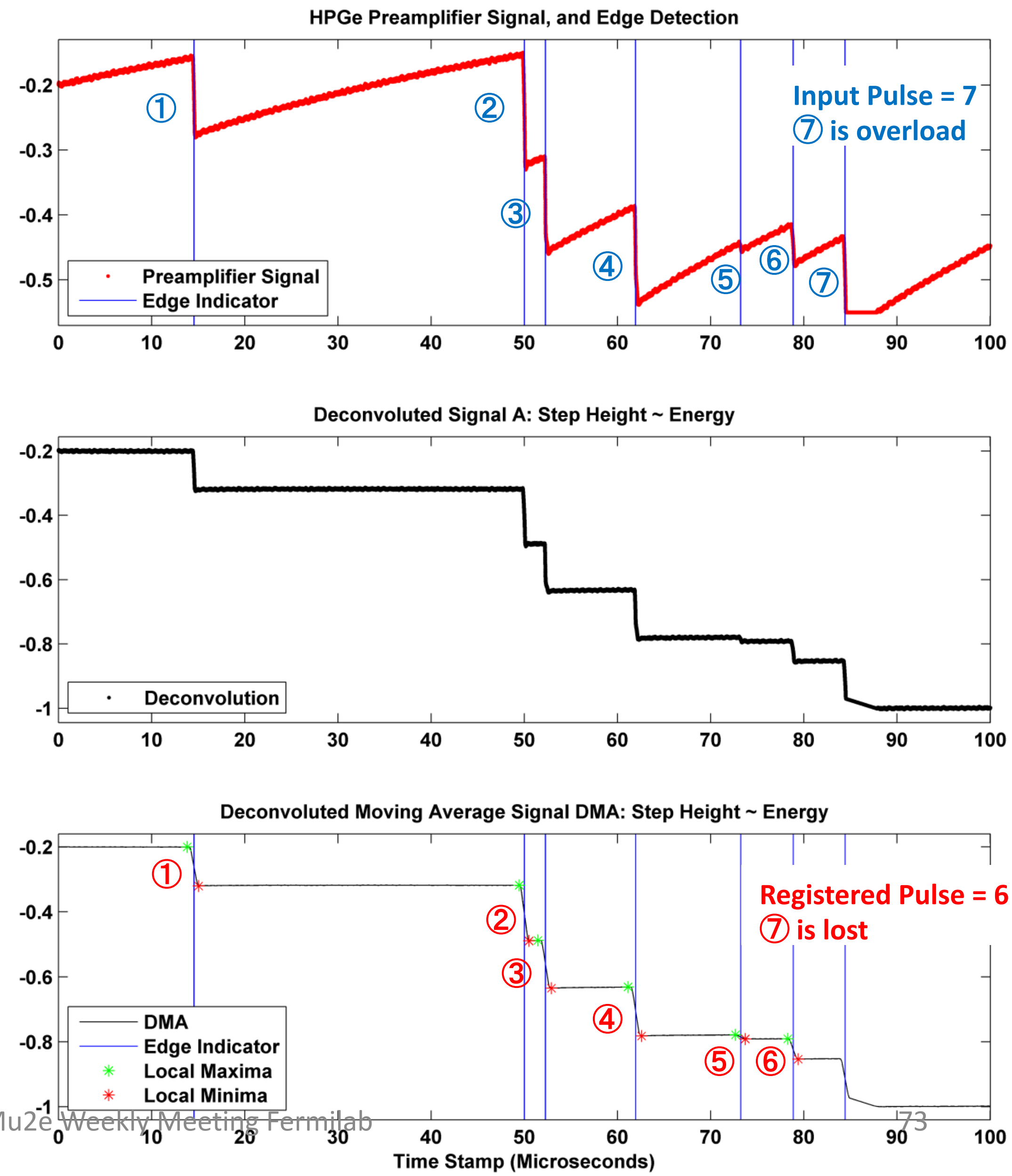


Dead time and Event Loss Issue: DMA

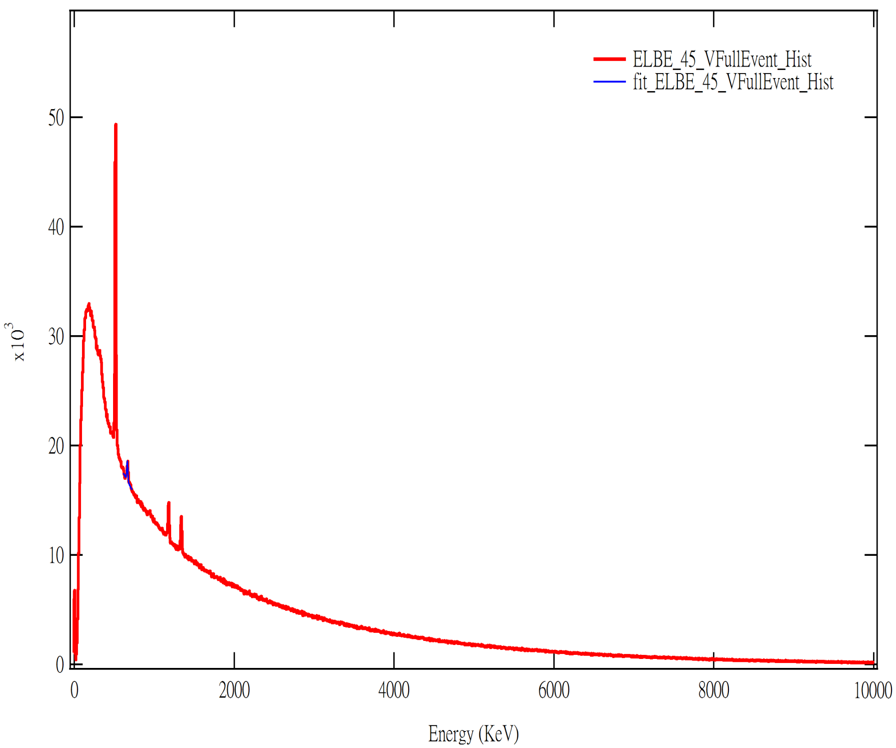
Example: DMA
Algorithm features
Leading Edge Distinction

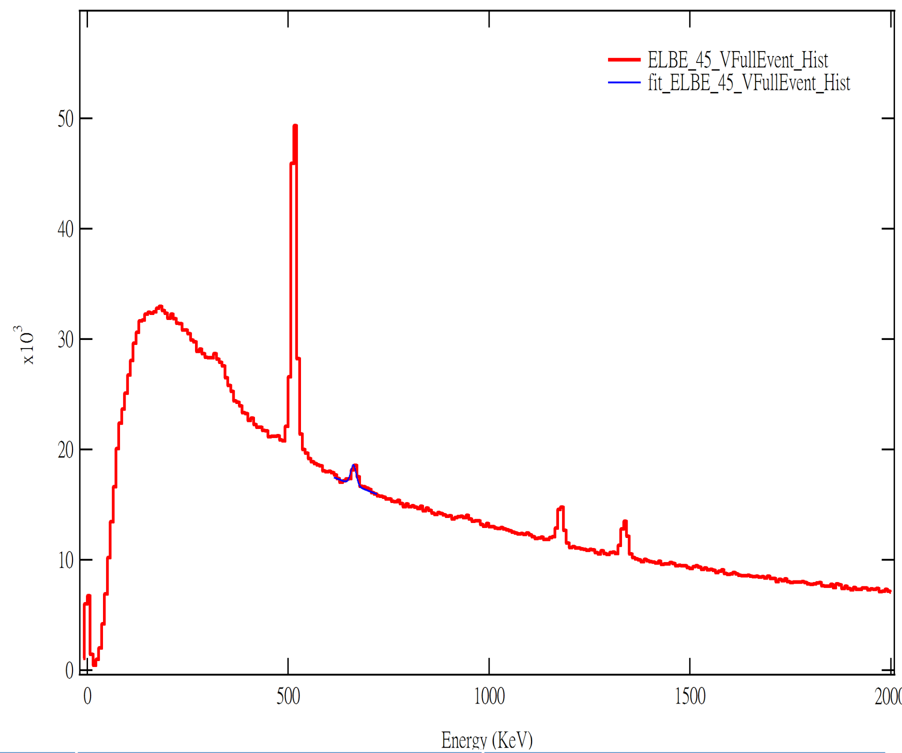
Step 1: Deconvolution

Step 2: Moving Average



ELBE_45 (72 kHz) DMAB-CFD





ELBE_45(72 kHz)		Liverpool		Purdue (Oscilloscope Data) MWD Algorithm		Purdue (Oscilloscope Data) DMAB Algorithm	
Source	Energy (KeV)	Sigma (KeV)	Err_Sigma (KeV)	Sigma (KeV)	Err_Sigma (KeV)	Sigma (KeV)	Err_Sigma (KeV)
Positronium	511	3.4	0.1	5.6	0.03	6.4	0.004
137Cs	661.62	3.5	0.05	N/A	N/A	7.1	0.06
60Co	1173.23	3.0	0.05	6.0	0.2	7.5	0.03
60Co	1333.51	3.0	0.01	7.7	0.3	7.8	0.04