H2020 Grant Agreement N° 690835

**Deliverable D2.3 – WP2 – Due date: 31st March 2018**

Title: Mu2e HPGe Design report

Type: Report

Dissemination level: Public

WP number: WP2

Lead Beneficiary: Liverpool

# Mu2e STM HPGe Detector Design Report.

*Dr Laura Harkness-Brennan and Daniel Judson*
*University of Liverpool*

## Design Requirements

The Mu2e experiment will search for neutrinoless muon-to-electron conversion, with the goal to test branching ratios up to $10^{-16}$, which is a factor of 10000 more sensitive than any previous experiment. Observations of a signal would be an example lepton flavor violation, which would require physics beyond the Standard Model. Mu2e will stop muons in an aluminum target, and will look for the mono-energetic electron produced in the reaction $\mu^- + ^{27}_{13}Al \rightarrow e^- + ^{27}_{13}Al$. In order to normalize the result, it is necessary to measure the number of stopped muons. A High-Purity Germanium detector (HPGe) will be employed to detect the number of characteristic muonic x-rays, or gamma rays produced when the muon stops in the target, which is directly proportional to the number of stopped muons. There are several important design criteria for the STM detector:

- **Energy resolution:** must be < 2 keV FWHM at 1.33 MeV, to resolve the desired photon lines from neighboring background gamma lines and to provide acceptable S/N above ambient background.
- **Count rate:** must be able to process the large flux (~150kHz) of photons entering the detector. This is challenging for commercially available detectors. When rates are too large, the energy resolution of the HPGe deteriorates and dead-time may also be introduced.
- **Timing performance:** The Mu2e muon beam is delivered in 200 ns wide pulses spaced at 1700 ns intervals (~600 kHz). Almost all the background gamma rate occurs at the time of the muon injection (we call it the 'flash'), while the photons of interest occur after that. The muonic x-rays are produced about 100-200 ns after the flash, while the gamma rays are produced throughout the period between pulses. The performance of the HPGe as a function of time after the flash is important to understand.
- **Peak to total:** In addition to the presence of background events from the flash, there will also be background from Compton scattered photons. These occur when the photons of interest (i.e. muonic x-rays or delayed gammas) deposit only a fraction of their energy and then leave the detector system. They cannot be used in the data analysis, complete energy deposition is required.

- **Cooling system:** The detector will need to be cryogenically cooled and the system will need to be compatible with the environment at Fermilab.
- **Overall size and shape:** There is only 3 feet of space along the beamline for the detector system to fit within.

To complete the design of the Mu2e STM, five relevant aspects of the detector have been studied in detail:

1. Rate studies at the γELBE facility in Dresden, Germany
2. Geant4 simulations of the HPGe detector crystal geometry
3. Analysis of cooling options
4. DAQ and readout
5. Collimation system

## 1. Rate Studies at the γELBE facility in Dresden, Germany

The unique characteristics of the pulsed photon beam at the γELBE facility was used to investigate the spectroscopic performance of a HPGe detector operating under high photon flux. Although the γELBE setup already contains HPGe detectors, we temporarily installed in the experimental cave an n-type coaxial Ortec GMX HPGe, which is a high purity germanium detector of the same configuration to be installed at Mu2e. The preamplifier signals were readout from the detector to a digital data acquisition system, which was a desktop CAEN digitizer. The preamplifier signals were digitised and stored for post-processing with digital signal processing (DSP) algorithms to determine the parameters that produce the optimum spectroscopic performance at high photon flux within a pulsed structure. Signals were also processed in real-time to produce photon spectra in-situ, to optimise the experimental setup. Photon spectra were acquired with the detector placed on the beam axis at the position indicated in Fig.1 within the γELBE experimental cave.

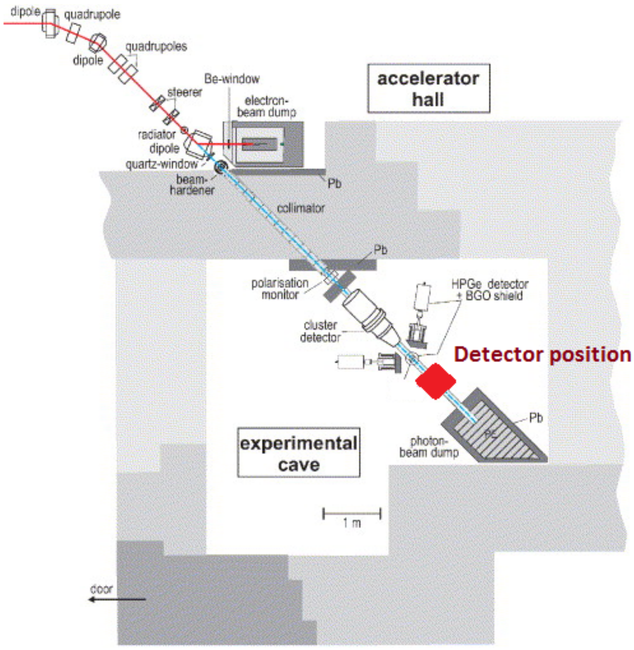



*Figure 1: Detector Position in ELBE Experimental Cave*

Data were initially acquired using calibration sources ($^{137}$Cs and $^{60}$Co) to calibrate the HPGe detector for energy and efficiency. Photon spectra were then recorded with the beam on and at various rates. Example spectra are shown in Figure 2. In the spectra, the 662 keV peak corresponds to $^{137}$Cs, the 1.1 and 1.3MeV correspond to $^{60}$Co,. When the beam is on, the 511 keV annihilation peak is also evident.

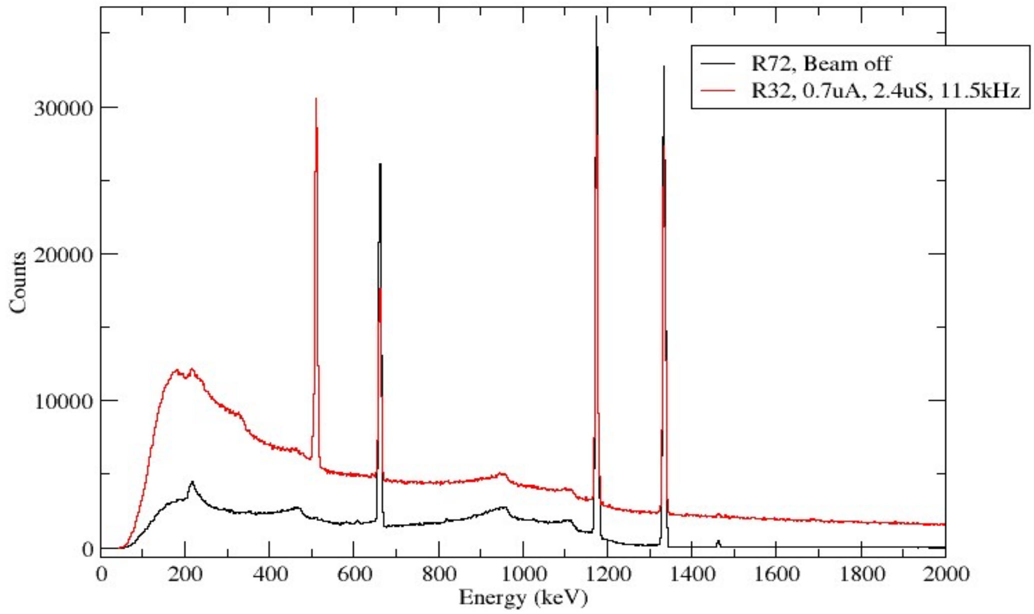



*Figure 2: Example beam on and beam off energy spectra of photons produced in the experiment.*

74 data runs were acquired. The data is being to measure the energy resolution, dead-time and recovery time as a function of photon flux. Rate performance will be tested with various photon rates range between 10 kHz and 100 kHz.   Results are shown here.

Figure 3 shows example spectra collected for various beam rates, for the detector in position 1.

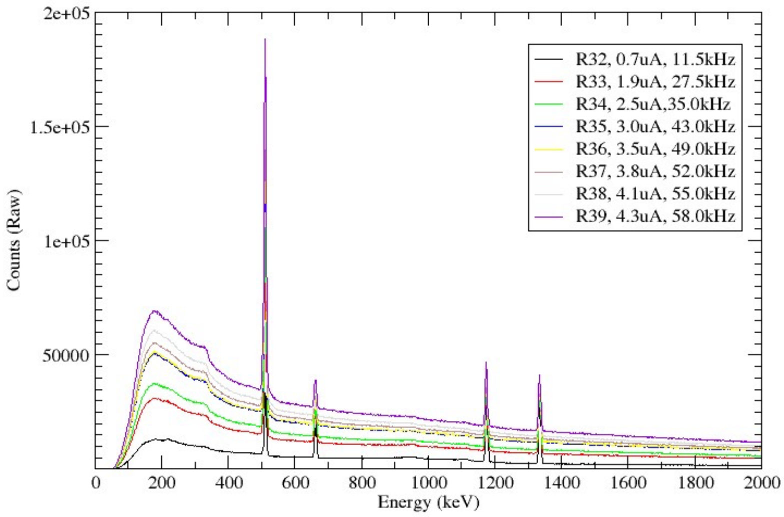



*Figure 3 Example energy spectra for various beam rates*

No significant degradation is observed for the runs shown in Figure 3. However, the background is increasing in each of them, due to the increased bremsstrahlung radiation production. It is easier to examine the shape of this background by plotting the spectra on a log scale, as shown in Figure 4. The shape of the distributions is very similar, just showing increased count rates according to increased beam rate, as expected.

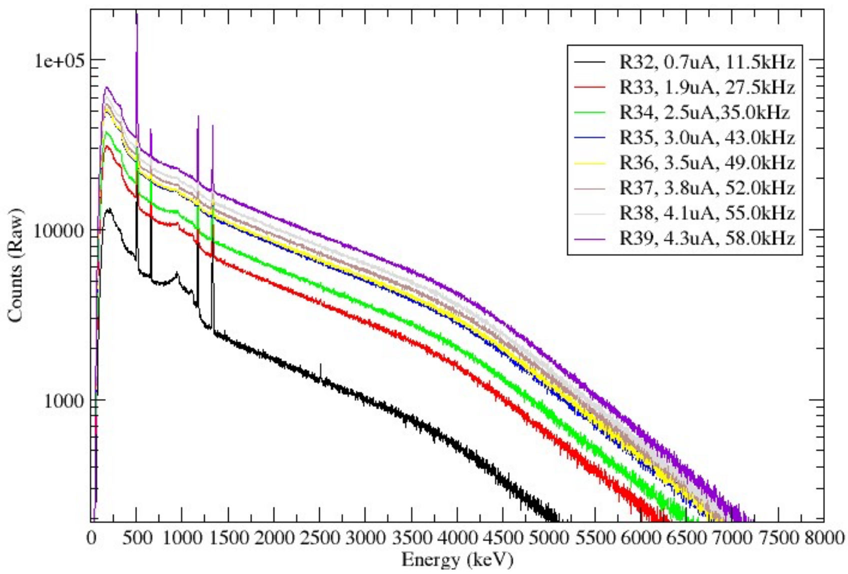



*Figure 4: Energy spectra (log scale) as per figure 3*

When the detector was moved into different positions, corresponding to different orientations, the shape of the spectra were observed to vary, as shown in Figure 5:

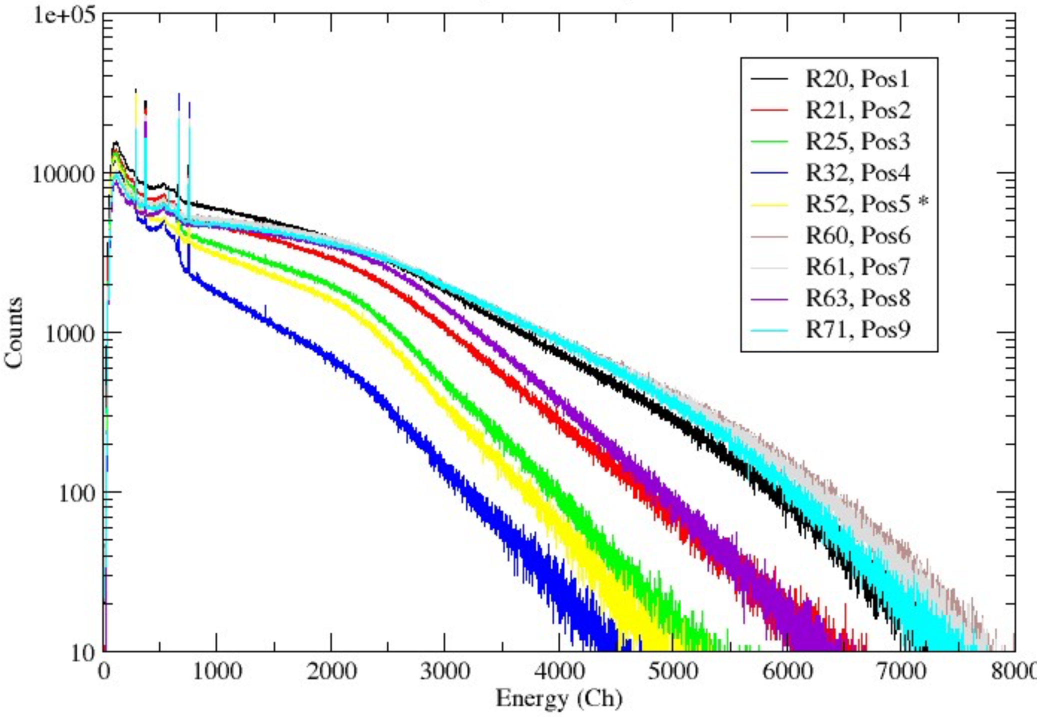



*Figure 5 Energy spectra for a fixed beam rate but with the detector in different orientations*

This data is under analysis but it is believed to be due to the beam passing through different "thickness" of germanium detector.

The timing performance of the detector will be very important in Mu2e. Therefore, the timestamp data from HZDR has been analysed. Figure 6 shows data for the first 1000 events, where the difference in time stamps between subsequent events, $ts_n - ts_{n-1} = \triangle ts$ has been calculated. The beam pulse structure of 9.85 microseconds can be seen, corresponding to the groups of events at around 1000, 2000, 3000 and 4000. The events between these groups are from background and the $^{137}Cs$ and $^{60}Co$ sources, which do not follow the beam structure.

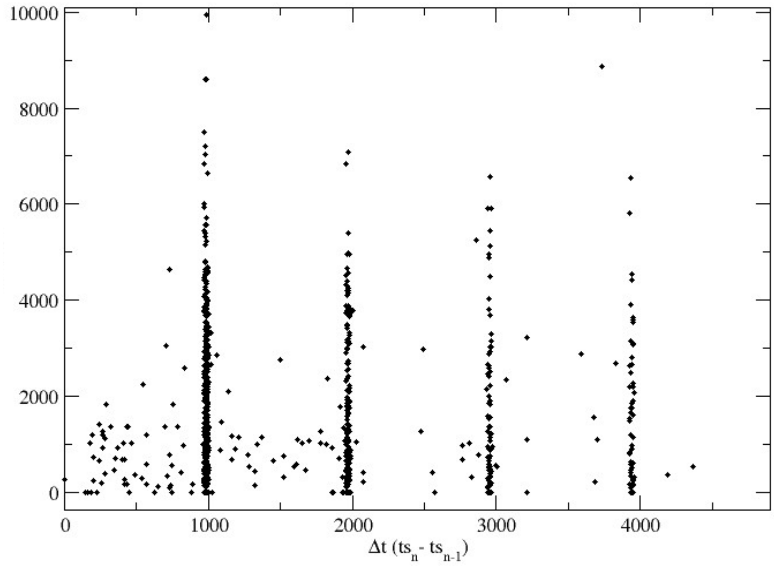



*Figure 6 Time stamp difference between events*

By gating on separate regions of Figure 6, it is possible to suppress events in the photon spectrum. Figure 7 shows a "zoomed" in version of Figure 6, with the region corresponding to +/200ns around the "beam" highlighted in red, and "out of beam" in green. The gated energy spectra for these regions are shown in Figure 8, where the suppression of beam events can clearly be seen (green spectrum).

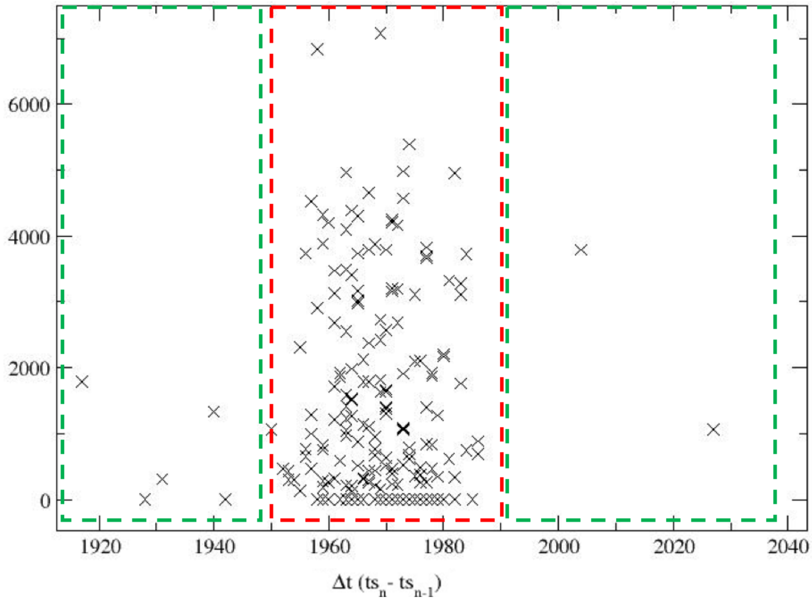



*Figure 7 Time stamp difference between events*

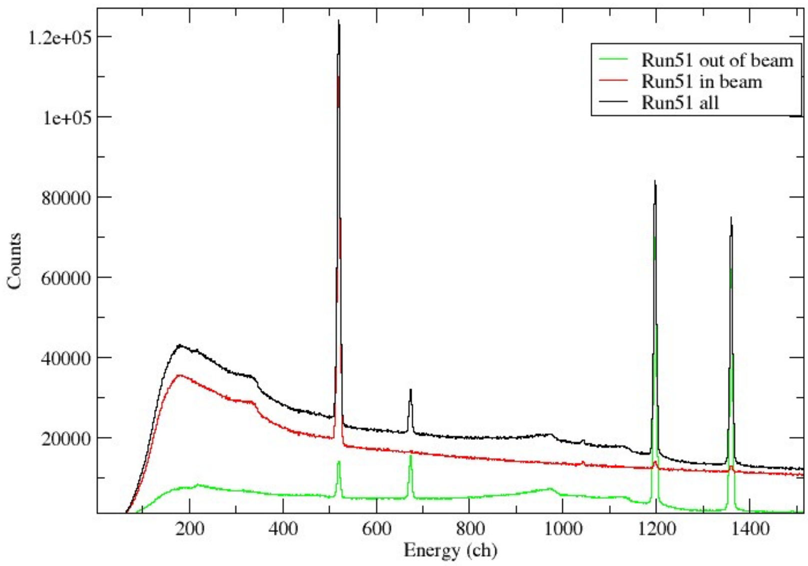



*Figure 8 Photon spectra gated on timestamp information*

The conclusions of this work can be sumarised as:

1. The photon peak energy resolution is not significantly degraded by the beam
2. The background in the spectra show strong dependence on detector position
3. Timestamps can be used to veto events in beam pulse, to suppress background and high rates

## 2. Geant4 simulations of the HPGe detector crystal geometry

Geant4 simulations have been undertaken to study the peak to total of various HPGe crystal geometries. A standard coaxial HPGe crystal can be described by Figure 9. The dimensions of interest are the diameter (A) and length (B) of the crystal, as well as the diameter (C) and length (D) of the bore hole.

It is not possible to constrain too much the geometry. The main optimisation challenges are:

- Crystals of given efficiency can have different crystal geometries – no fixed bore/crystal diameter/length
- Bore hole size increases with the number of manufacturing processes – constraining it will increase costs.

Therefore, some example Ortec n-type (GMX) detectors were modeled using Geant4, to understand the performance variation. Five detector types were chosen because they either had full spec sheets (GMX90, GMX70 d1 and GMX70 d2) or limited spec sheets in which no bore hole information was provided (GMX45 and GMX23). Geant4 simulations of 1cm$^2$ beam of gammas incident on front face of detector, at various radii (assumes 100% collimation) were undertaken for the following primary event conditions:

- Brem spectrum with no degrader (434873 events)
- Brem spectrum with 10mm Pb degrader (136971 events)
- Brem spectrum with 170mm Poly degrader (145995 events)
- 347 keV only ($10^5$ events)
- 844 keV only ($10^5$ events)
- 1.809 MeV only ($10^5$ events)

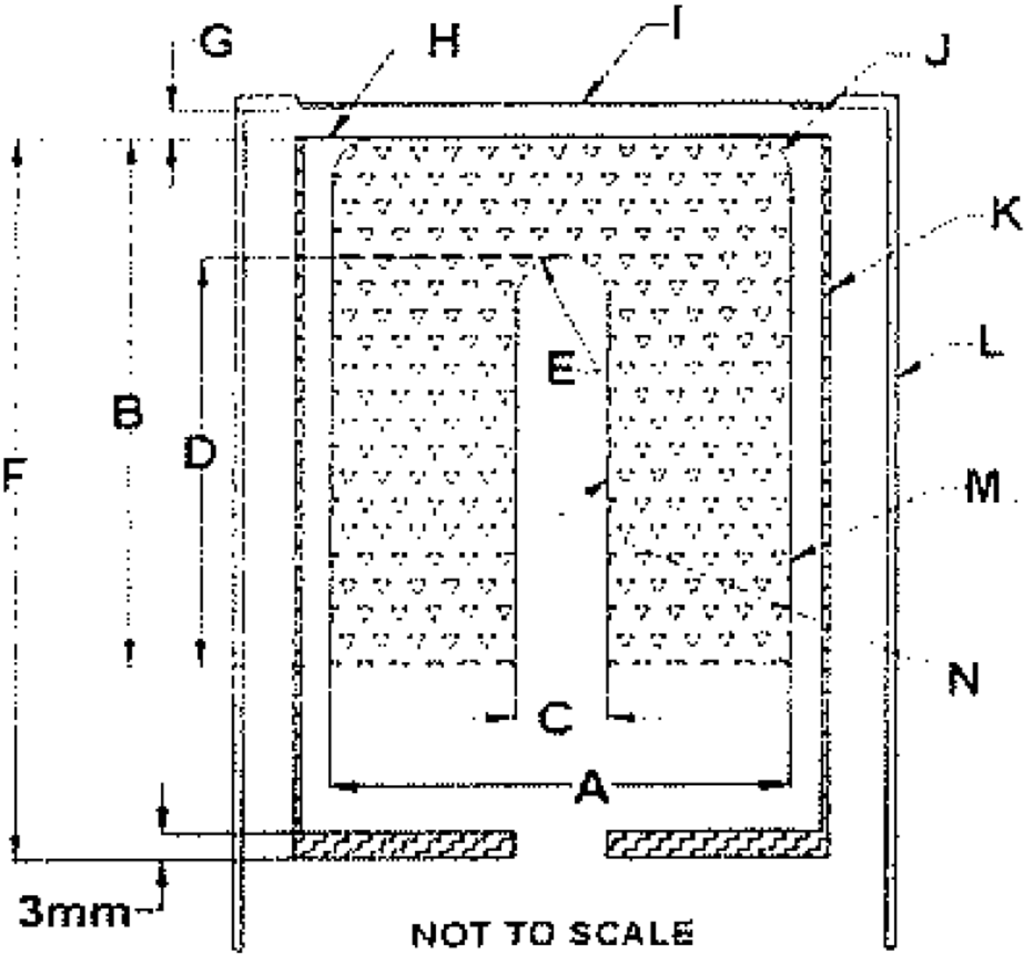



*Figure 9 General drawing of a HPGe detector (Ortec Website)*

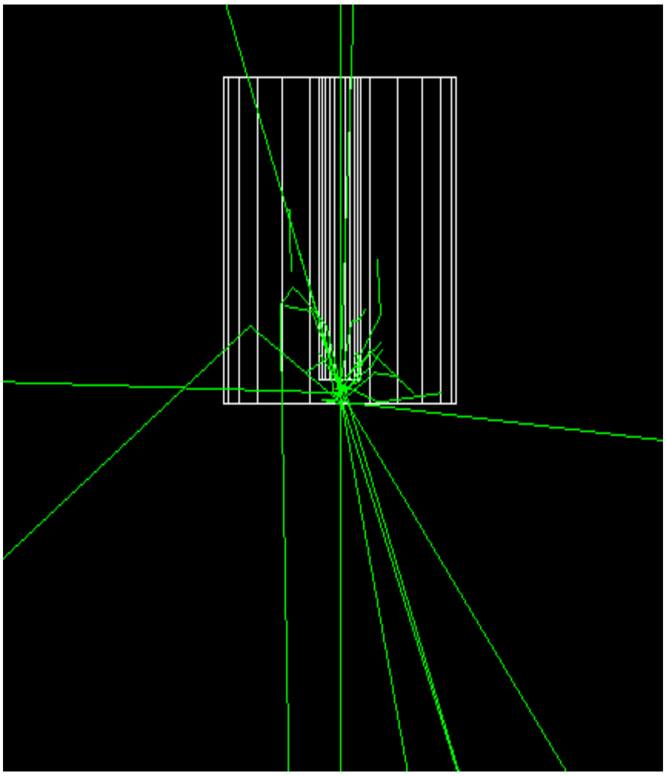


*Figure 10 Visualisation of a GMX detector and first 10 events*

Once the data were acquired a number of metrics were investigated:

1. Total % Brem photons interacting in the detector (for each of the degraders), as a function of beam position (given as radial distance from centre of the detector)
2. Total 347 keV photons interacting in the detector (depositing any energy), as a function of beam position (given as radial distance from centre of the detector)
3. Total 347 keV photons interacting in the detector (depositing 347 keV), as a function of beam position (given as radial distance from centre of the detector)
4. Total 844 keV photons interacting in the detector (depositing any energy), as a function of beam position (given as radial distance from centre of the detector)
5. Total 844 keV photons interacting in the detector (depositing 844 keV), as a function of beam position (given as radial distance from centre of the detector)
6. Total 1809 keV photons interacting in the detector (depositing any energy), as a function of beam position (given as radial distance from centre of the detector)
7. Total 1809 keV photons interacting in the detector (depositing 1809 keV), as a function of beam position (given as radial distance from centre of the detector)

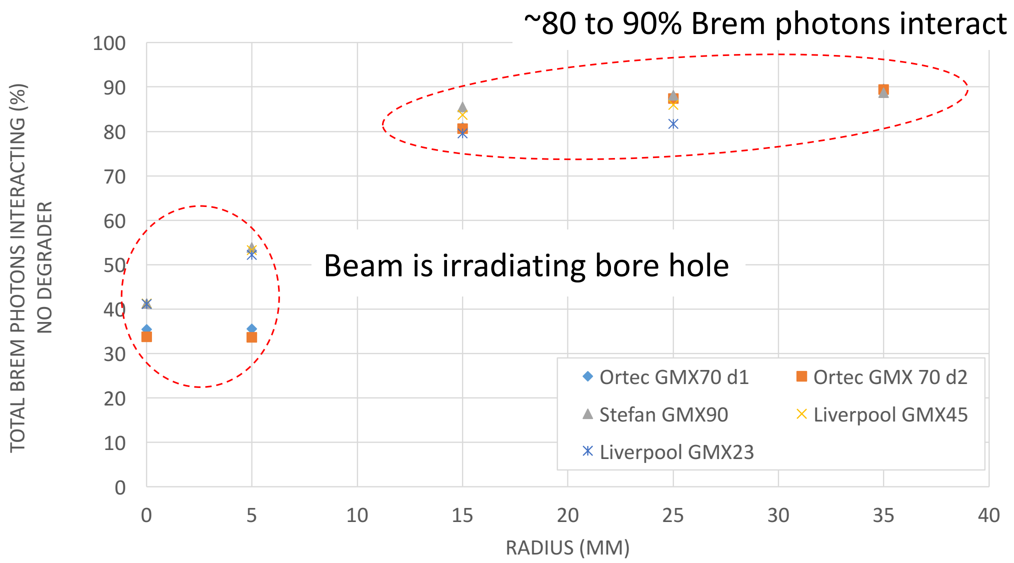



*Figure 11 Total Brem photons interacting as a function of radius, for various GMX detectors, no degrader*

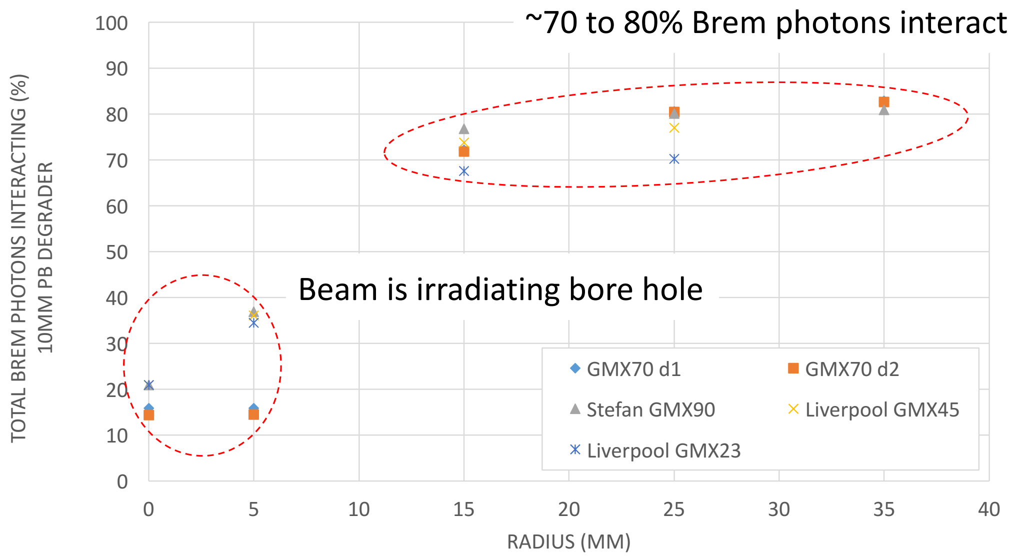



*Figure 12 Total Brem photons interacting as a function of radius, for various GMX detectors, 10mm Pb degrader*

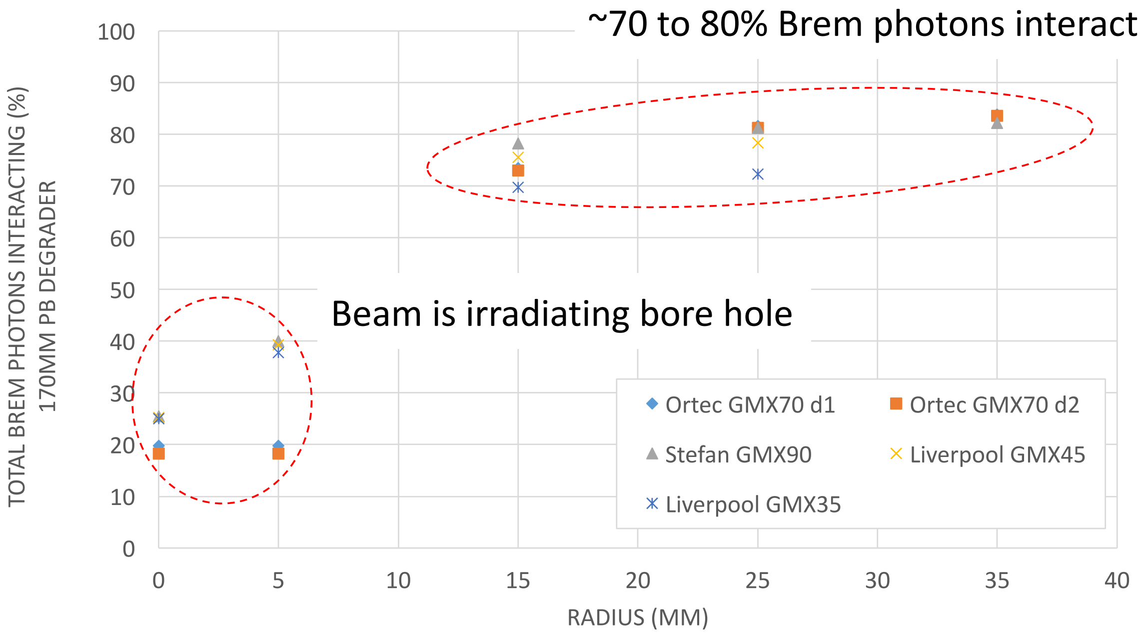



*Figure 13 Total brem photons interacting as a function of radius for various GMX detectors, 170mm Poly degrader*

From the results, beam position was fixed at r=15mm for GMX70 d1, GMX45 and GMX23, otherwise r=20mm was used. The efficiencies for each of the photon energies could then be calcualted for these "optimum" beam positions:

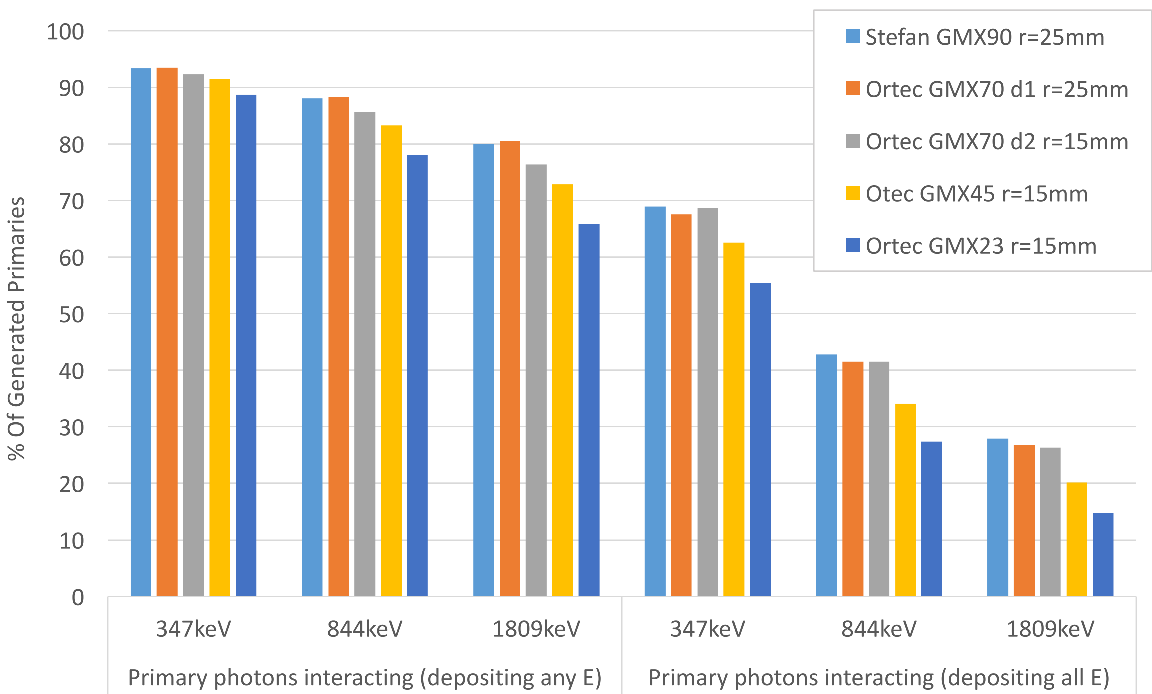
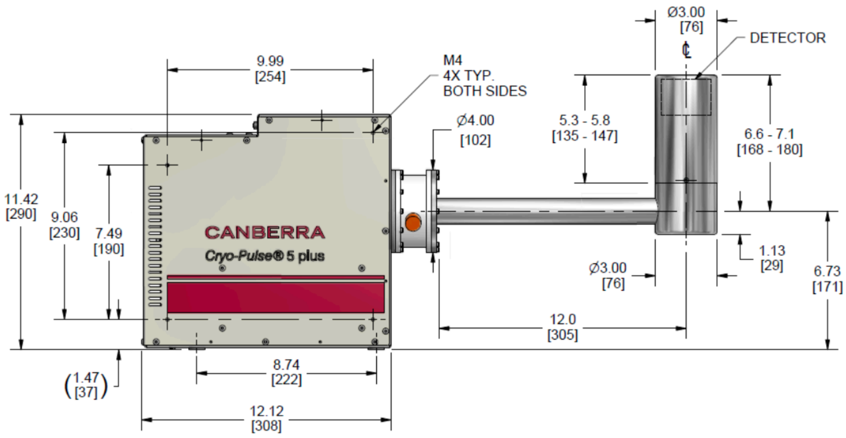



*Figure 14 Detector efficiencies for the various detectors and 3 photon energies of interest. Only those photons that deposit all E will be used in analysis.*

It can be seen that at 347 keV, the detectors have efficiencies between 55 and 68%, at 844 keV between 27 and 43% and at 1809 keV between 16 and 28%. It is therefore recommended that an altnerative, more efficient detector is used to detect the 1809 keV. The GMX23 is too small to be usedful but the GMX90 is no more useful than the GMX70. It is recommended to undertake further analysis of data around GMX45 to GMX75.

## 3. Analysis of cooling options

It will be (practically) difficult to anneal the detector in-situ and to cool it using liquid nitrogen. Servicing it will be inconvenient. Therefore, an electrical cooler will be purchased. Only a small number are available. The GP5-PLUS-U Canberra option has been identified as promising because it allows electrical cooling with a right-angled cold finger. The benefit of the right-angled cold finger is that the cooler will not be in the beam line, which is advantageous in the tight space and to reduce scattering materials. A screenshot from the Canberra brochure is shown:




**CP5-PLUS-U Electrically-Cooled Cryostat (side view)**

## 4. DAQ and read-out

A first design of the DAQ/readout using an FPGA-based TDC and a FPGA readout board has already been reviewed at FNAL and a test-stand has been established at UCL and also at FNAL where it has been interfaced to a prototype clock and control distribution system. The version of the Moving-Window-Deconvolution (MWD) pulse finding algorithm applied to the beamtest data is presently being translated into firmware.

## 5. Collimation system

The design of the collimation system which reduces the radiation damage to the STM, while ensuring a sufficient number of X-rays to be recorded, comprises of two components: a field-of-view collimator and a spot-size collimator. The former, a 15 cm long, 45 cm thick lead collimator with an aperture of approximately 7 cm, has jaws that are movable in the x and y directions, and ensures the STM has a line of sight to the aluminium stopping target only and not to other components that would affect the X-ray rate. This is located 34 m upstream of the STM after the main detector systems and a so-called sweeper magnet used to remove low energy electrons. The spot-size collimator is a 15 cm thick tungsten disk with a 5 mm opening that is rotated across the face of the detector such that the detector can be uniformly irradiated and operated for several months without annealing. The collimators must be controllable remotely and reliably and interface to the FNAL-wide interlock and control system (iFix).

## Conclusions

The main conclusions of the study are:

- HPGe detector shown to operate up to 100KHz without degradation in energy resolution
- Brem flash has position dependence in detector
- An n-type 70% HPGe crystal will be sufficient for efficiency. It is not desirable to increase the detector size as there is no real increase in photon efficiency but the detection of bremmstrahlung increases, which will cause dead time and throughput issues.
- Electrical cooler CP5-PLUS-U is an ideal cooling option for the detector