Tests of the detector system for the Stopping Target Monitor of the Mu2e experiment in a high flux pulsed gamma beam

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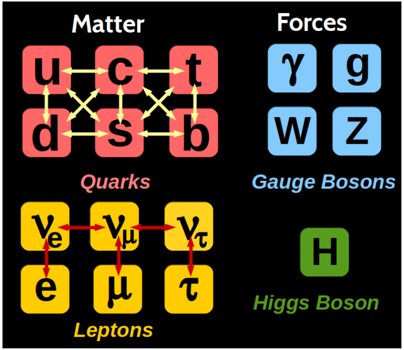
Motivation

The Standard Model of particle physics currently contains:

- Quark mixing
- Transitions between charged and neutral leptons of same flavor
- Neutrino oscillations



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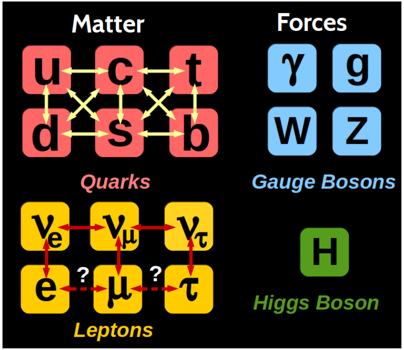
No charged lepton flavor violation (CLFV) observed so far!



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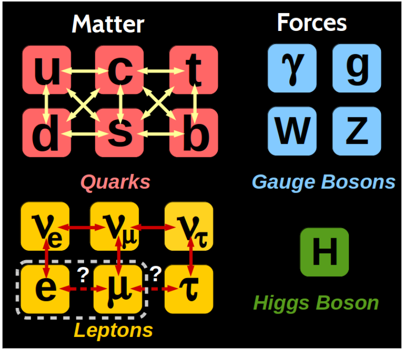


Mu2e will search for the neutrinoless conversion of a muon into an electron in the coulomb field of a nucleus ($\mu N \to eN$) with a projected

upper limit of 6×10^{-17} (90% CL)

Current limit by SINDRUM-II (PSI): $B(\mu Au \to eAu) < 7 \times 10^{-13}$(90% CL)

SM prediction via neutrino mixing is $\sim 10^{-54}$, but extensions of SM predict values up to $\sim 10^{-14}$ (Leptoquarks, heavy neutrinos, SUSY,...)

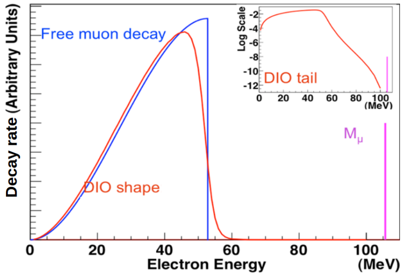
$\Rightarrow$ Unique possibility to test for New Physics

The Mu2e experiment

The **Mu2e** experiment will search for CLFV in the process ($\mu^- + \text{Al} \rightarrow e^- + \text{Al}$)

Stopped muons have a lifetime of 864ns in the 1s-orbital of the Al nucleus

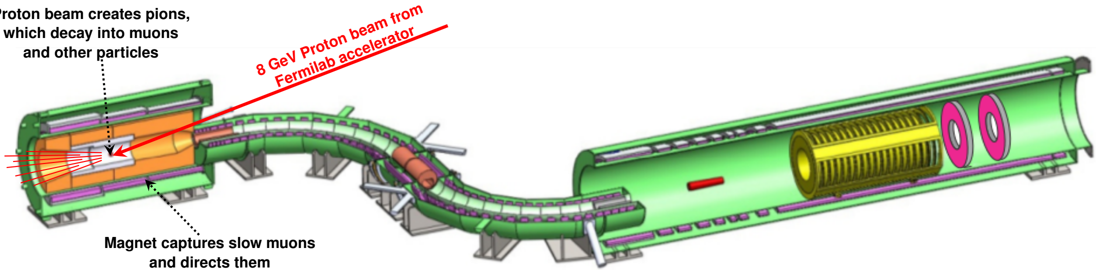
- about 60% of stopped muons undergo the muon capture reaction (e.g. $\mu^- + {}^{27}\text{Al} \rightarrow \nu_\mu + {}^{27}\text{Mg}$)
- $\sim$ 40% of stopped muons decay in orbit (DIO)
  - Michel spectrum of decay electrons dies around $M_\mu/2$
- CLFV signal for $\mu \rightarrow e$ conversion gives single mono-energetic electron
  - $E_e = 104.973\ \text{MeV} \simeq M_\mu$



$$\text{Normalized ratio } R_{\mu e} = \frac{N(\mu^- + \text{Al} \rightarrow e^- + \text{Al})}{N(\mu^- + \text{Al} \rightarrow \text{nuclear capture})}$$

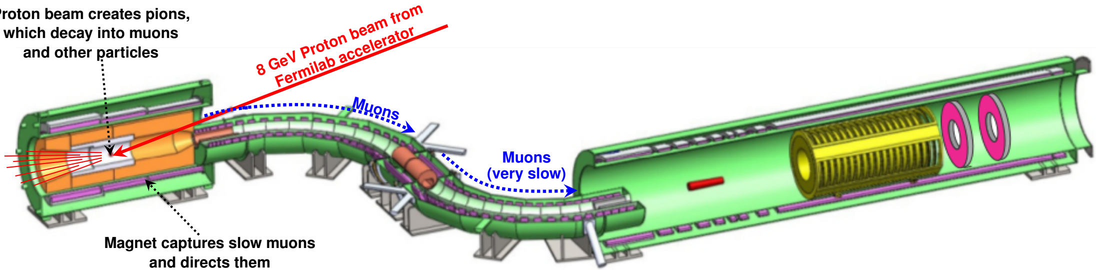
HZDR

The Mu2e experiment



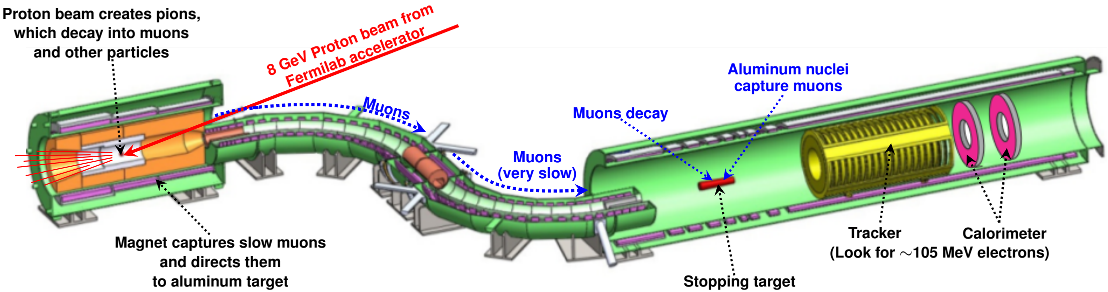
- Muons are obtained from 8 GeV proton beam on tungsten target
  - time-averaged beam power: 7.3kW
  - 4×10^7 protons/pulse, pulse separation: 1695ns
  - Magnetic field in Production Solenoid guides produced pions towards Transport Solenoid
  - Pions decay into muons

The Mu2e experiment



- Muons are transported in s-shaped Transport Solenoid
  - Absorber foils remove antiprotons
  - Solenoidal magnetic fields separate oppositely charged particles
  - Collimators select low-momentum negatively-charged muons.

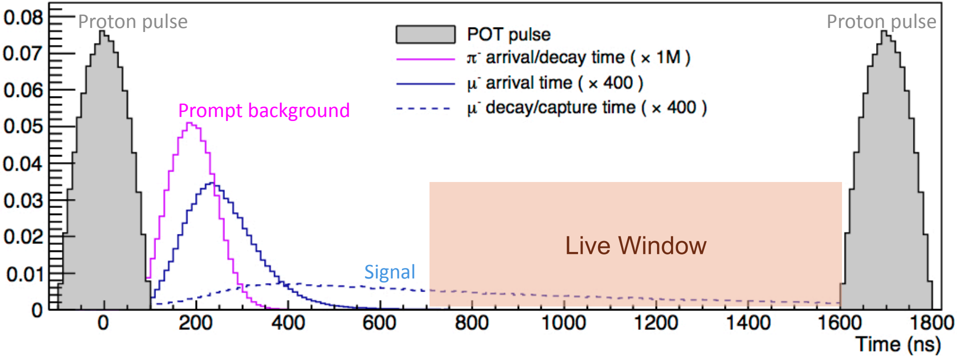
The Mu2e experiment



- Muons are stopped on aluminum target foils in Detector Solenoid
  - stopped muons decay in orbit or are captured by the Al nucleus
  - decay electrons are detected by a tracking detector and a calorimeter

The Mu2e experiment

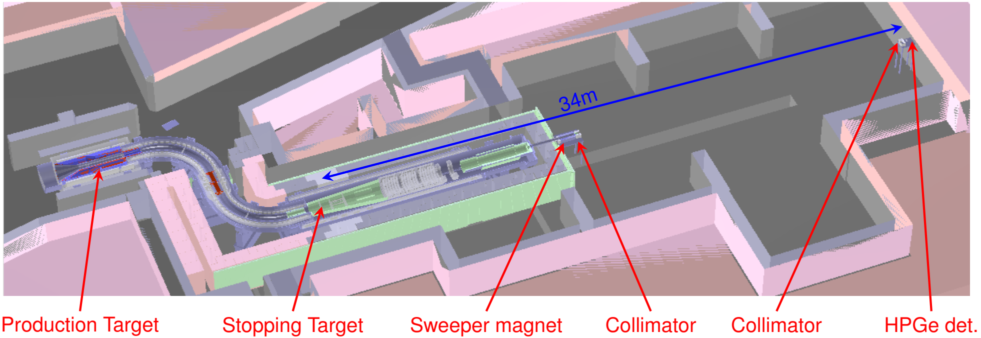
Pulsed proton beam allows definition of a “Live Window” for the signal to suppress prompt back-ground (1695ns peak-to-peak):



- Fermilab accelerator complex provides optimal pulse spacing for Mu2e
- 700 ns delay allows to suppress prompt background from pions by $\sim 10^{-11}$
- Must achieve extinction (N_{p^+} out of bunch)/(N_{p^+} in bunch) $\leq 10^{-10}$

The Stopping-Target Monitor

High-purity Germanium detector to determine overall muon-capture rate on Al to the level of 10%

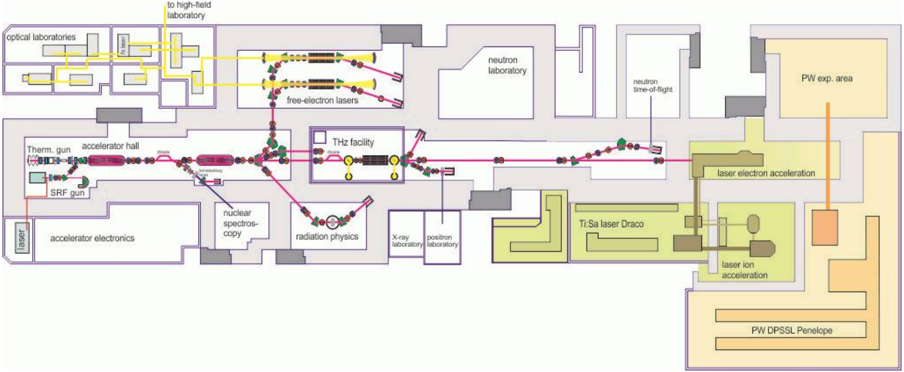


- measure X- and γ-rays from muonic Aluminum
  - 347 keV 2p-1s X-ray (80% of muon stops)
  - 844 keV delayed γ-ray (5% of muon stops)
  - **1809 keV** γ-ray (30% of muon stops)
- line-of-sight view of Muon Stopping Target
- sweeper magnet to reduce charged particle background and radiation damage to detector
- It was decided to accompany the HPGe detector with a $LaBr_3$ detector (worse energy resolution, but can take higher rates)

Mu2e@HZDR: The ELBE radiation source

The ELBE “Electron Linac for beams with high Brilliance and low Emittance” delivers multiple secondary beams.

- $E_e \leq 40$ MeV; $I_e \leq 1$ mA; Micropulse duration 10 ps $< \Delta t <$ 1 μs



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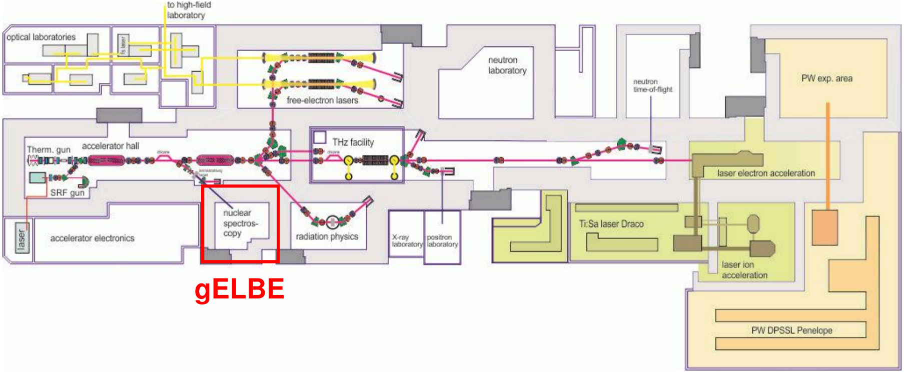
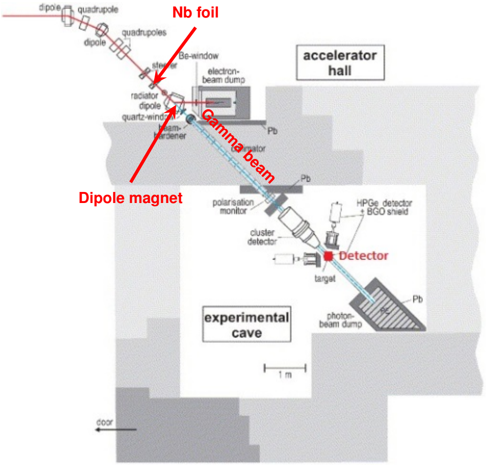


gELBE: Bremsstrahlung gamma beam facility

Studying HPGe & $LaBr_3$ detector response at gELBE

gELBE utilizes bremsstrahlung production from an electron beam impinging on niobium radiator foils. A dipole magnet sweeps away charged particles in the beam.



Studying HPGe & $LaBr_3$ detector response at gELBE

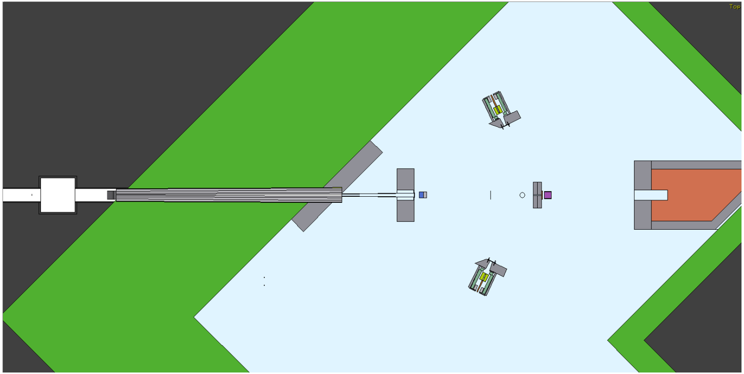
Use of gELBE's pulsed bremsstrahlung γ-beam with max. energy of 15 MeV.

- The muons hitting the aluminum disks of the Stopping Target will produce a bremsstrahlung "flash" background on top of which one needs to detect the characteristic lines emitted when the muons stop or are captured
- gELBE pulse separation of 1.23μs or 2.46μs close to Mu2e's 1.7μs proton pulse separation
- 150kcps of gamma rates expected for Mu2e Stopping-Target Monitor detectors during nominal beam pulse
  - high average γ energy ($\sim$ 5 MeV)
  - high beam pulse occupancy ($\sim$ 20%)
  - large beam intensity fluctuations might occur (up to a factor of 6)
- Use of calibration sources (^{137}Cs, ^{60}Co, ^{88}Y) together with the pulsed bremsstrahlung spectrum of gELBE allows to simulate Mu2e conditions

Beamline simulations with FLUKA:

The gELBE beamline has been modeled using the FLUKA program package

- Simulate gELBE bremsstrahlung spectrum starting from electron beam hitting niobium foil and propagate it to detector position
- Detector behind lead wall with 1cm^2 collimator hole and copper/aluminum absorber plates to shield from lead fluorescence.



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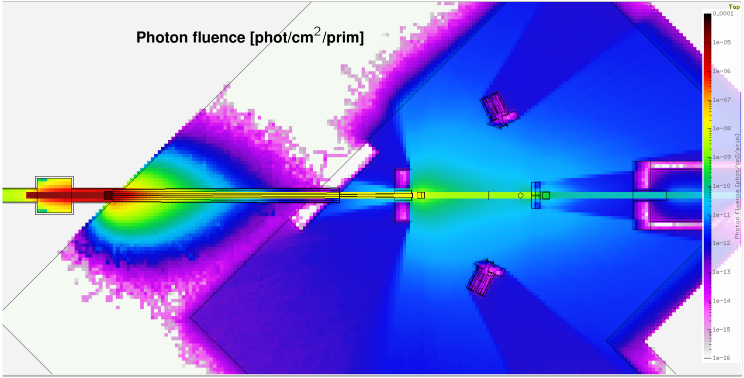

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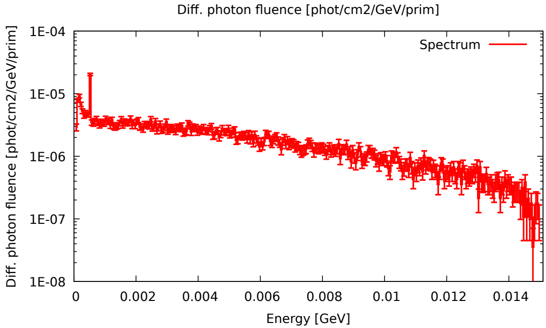
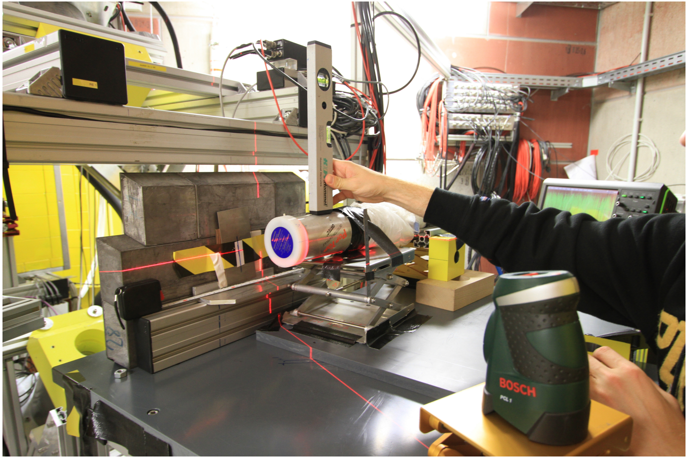


August 2017: Test of a HPGe detector

The aim of this beamtime was to measure HPGe detector performance in the **gELBE** beam in terms of energy resolution and radiation damage and to understand the best detector geometry and position. Also the effect of absorbers (Pb, Cu, Al) was investigated.



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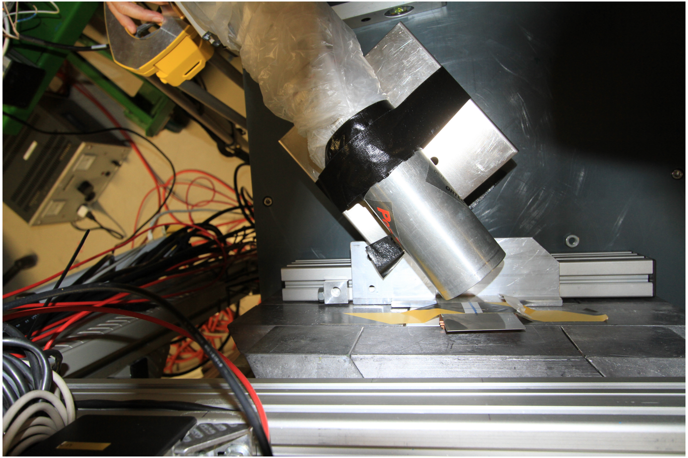

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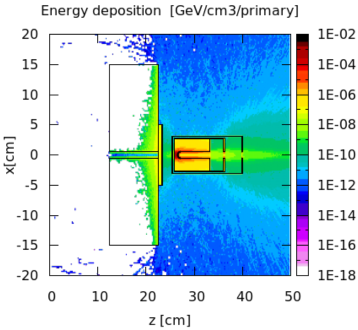
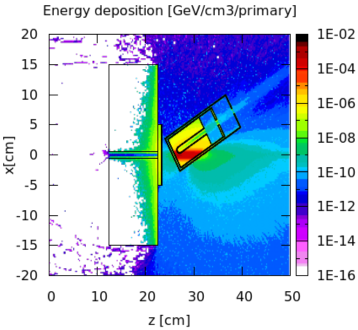
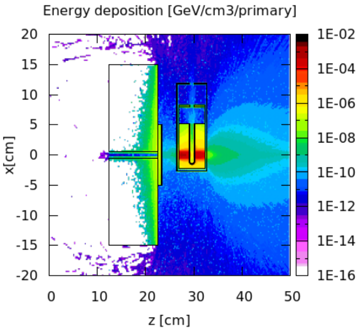
The energy deposition in crystal was studied using **FLUKA**:



Average energy deposition (508.68±0.11) keV per primary γ



Average energy deposition (1846.3±0.16) keV per primary γ



Average energy deposition (1759.4±0.08) keV per primary γ

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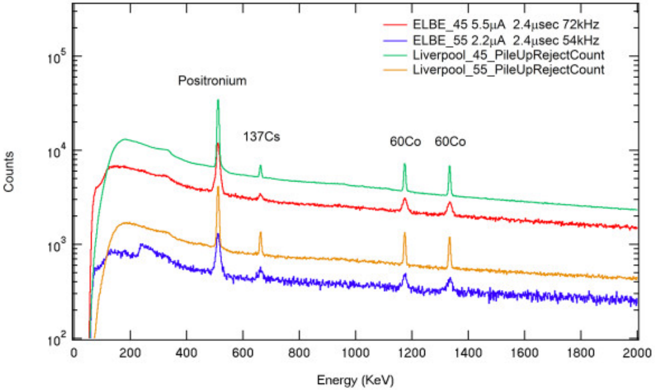
Analyzed spectra by applying Moving Window Deconvolution algorithm:



Energy resolution from spectrum analysis between 3 KeV (Liverpool) and 6 KeV (Purdue).

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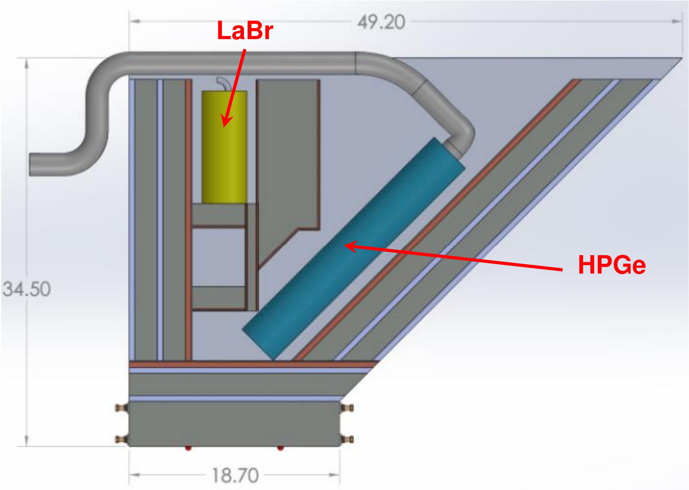
- No radiation damage on detector found after beamtime
- No degradation in energy resolution after beamtime
- The data has been used to exercise and test reconstruction algorithms
- Observation of single spectral lines over high-rate bremsstrahlung background with high average photon energy is possible

As an outcome of this beamtime, the HPGe detector specifications where finalized and two HPGe detectors have been acquired for use at the **STM** by the Liverpool group.

The Stopping-Target Monitor shieldhouse design

The outcome of this first beamtime also helped to design the STM shieldhouse. HPGe detector needs to be in an angled position due to limited space. Detectors “see” the Aluminum stopping target through collimator holes in tungsten shielding block.

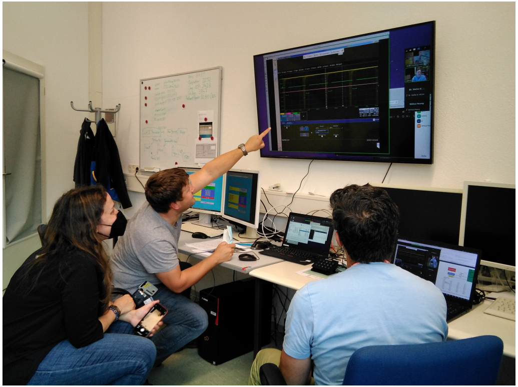


HZDR

Sept 2021: Test of the $LaBr_3$ detector

The goal of this beamtime was to test whether the $LaBr_3$ detector system can deal with the rate fluctuations anticipated at the Mu2e experiment.

Detector was shipped from Purdue University to Dresden and set up by the HZDR experimental team (FWK, FWCC, FWOR). Purdue colleagues were connected via video link (set up by FWK IT).



Sept 2021: Test of the $LaBr_3$ detector

A calibration source including Y-88 line at 1836 keV was used to mimick the muon capture on Aluminum emission at 1809 keV.

$\rightarrow$ determine energy resolution for 1836 keV line over Bremsstrahlung spectrum at increasing levels of **gELBE** electron current

Streaming mode: Take data at 406 kHz and 813 kHz pulse frequency at 500 MHz sampling with increasing electron current (for 813 kHz, overlay a 0.2s-on/4s-off window to protect PM tube)

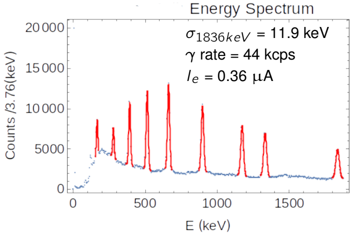
Veto mode: Take data at 813 kHz and 1625 kHz pulse frequency at 500 MHz sampling with increasing electron current, overlay a 0.2s-on/4s-off window and veto the Bremsstrahlung pulses to bring the “flash” background down

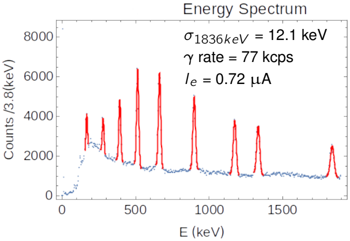
“Nominal” expected **Mu2e** conditions were found at a pulse frequency of 813 kHz and 1.1 uA electron current:
150 kcps with 3.8 MeV average photon energy.

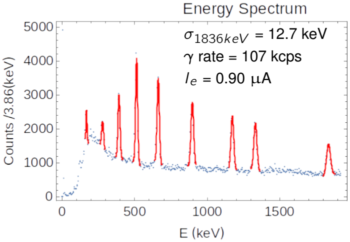
HZDR

Sept 2021: Test of the $LaBr_3$ detector - Prel. results

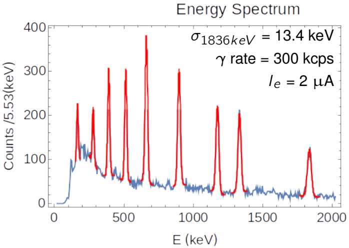
Data taken in streaming mode shows stable energy resolution (406 kHz pulse frequency):







Detector system can handle date taken at twice the expected photon rate (813 kHz pulse frequency):



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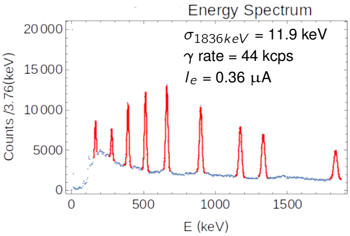
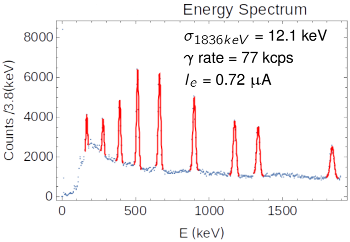
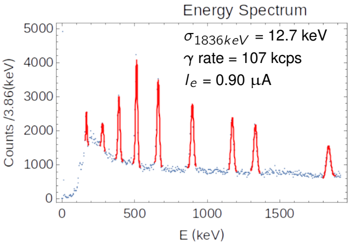
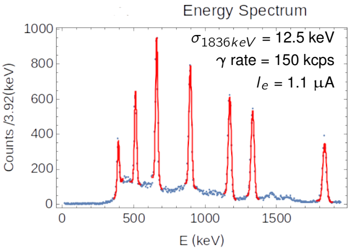






Data taken in veto mode shows that detector system can handle the rates using the pulse veto to suppress “flash” background (813 kHz pulse frequency):



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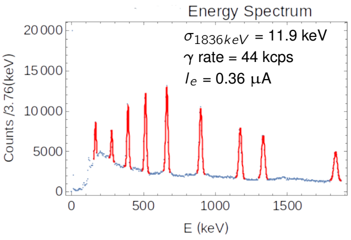

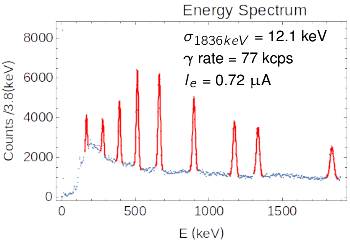

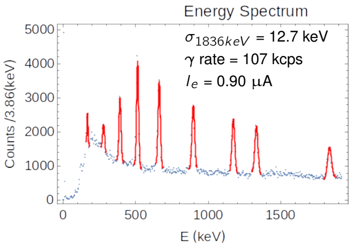

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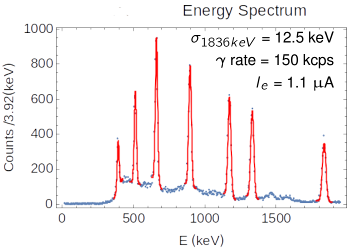


The origin of a time-dependent gain drift in the runs with 0.2s-on/4s-off structure still to be understood (for $t > 5$ ms).

April 2022: Test of FPGA-based DAQ system

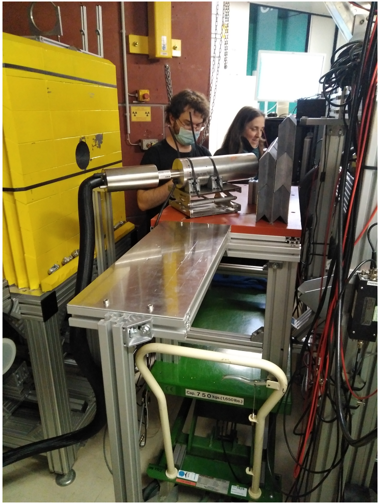
This beamtime was used to test the FPGA-based data acquisition system of the two detectors (HPGe and $LaBr_3$), which was developed by Mu2e-colleagues in the UK. In addition, further characterization was carried out for the $LaBr_3$ detector system.

- One of the two Liverpool HPGe detectors and the DAQ system were brought to HZDR
- Redesigned PM-base was sent from Purdue University
- UK team present at HZDR (3 x Manchester, 3x London, 2 x Liverpool)
- Purdue team connected remotely
- Local HZDR team from FWK, FWCC and FWOR

The beamtime received funding from the **RadNext**-Network

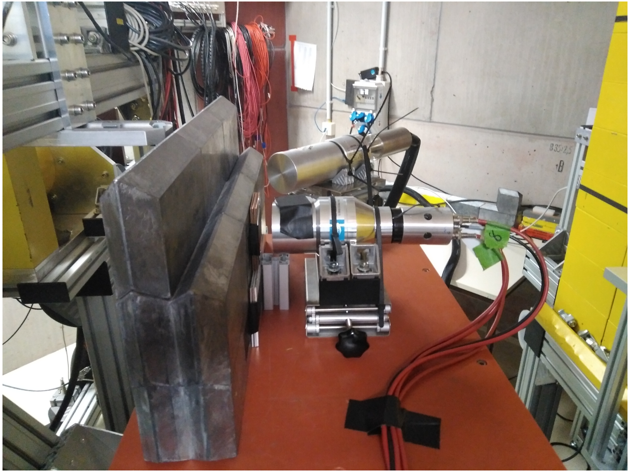
April 2022: Test of FPGA-based DAQ system

Setting up the **HPGe** detector in the **gELBE** cave:



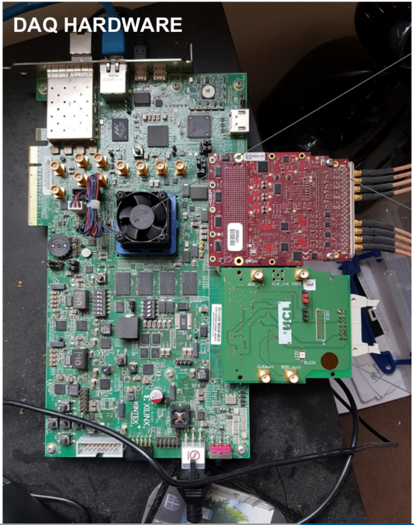
April 2022: Test of FPGA-based DAQ system

$LaBr_3$ and **HPGe** detectors in the **gELBE** cave:



April 2022: Test of FPGA-based DAQ system

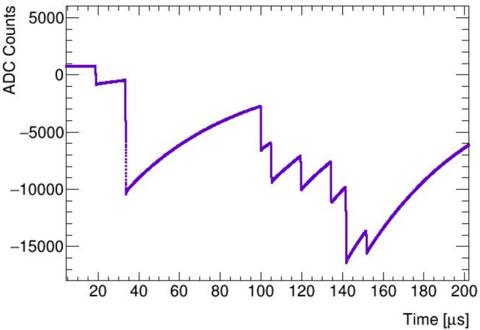
FPGA-based DAQ readout system:

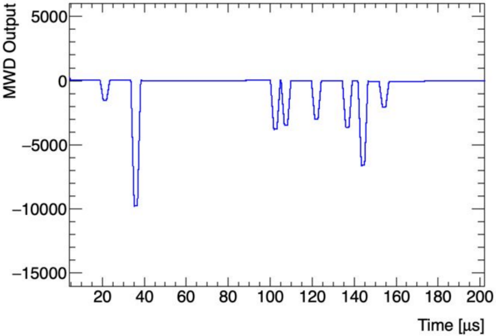


- Xilinx Kintex-7 FPGA board with 2 FMC connectors and two fibre-links
- 4 channel ADC mezzanine card
- Second mezzanine card for clock and trigger inputs

April 2022: Test of FPGA-based DAQ system - Prel. results

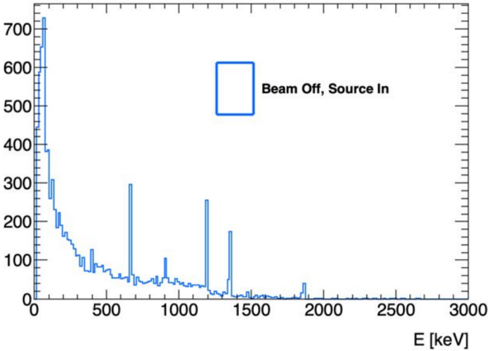
Raw data streamed to server via fibre-link without online pre-processing (e.g. no zero suppression applied). “Moving-Windows-Deconvolution” (MWD) algorithm applied offline:

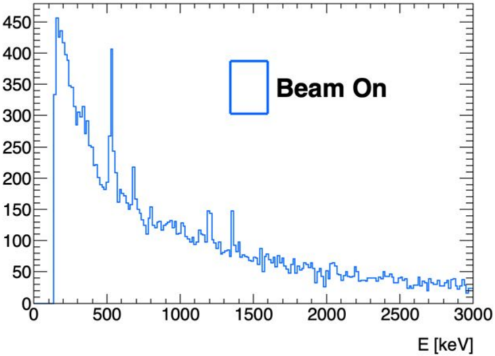




April 2022: Test of FPGA-based DAQ system - Prel. results

Data was taken under different conditions: beam+source, just source, no beam and beam at different gELBE currents (with both detectors).





An issue of dropped packets was found (but has in the meantime been cured in a new version of the DAQ code).

Summary & Outlook

The detectors of the Stopping Target Monitor (STM) of the Mu2e experiment have been tested at the gELBE beamline

- First beamtime in August 2017:
  - Characterization of HPGe detector, design of STM shielding house
- Second beamtime in September 2021:
  - Test of $LaBr_3$ detector's response to anticipated Mu2e beam fluctuations
- Third beamtime in April 2022:
  - Further tests with the $LaBr_3$ detector
  - Testing the DAQ chain for HPGe and $LaBr_3$ detectors

We would like to thank the **ELBE** team, and in particular beamline scientist Roland Beyer!

Detectors will now be shipped to FNAL, where they will undergo further testing before installation.

With a first run of physics data taking starting in 2026, Mu2e will either unambiguously discover CLFV or push the limit on muon $\rightarrow$ electron conversion by four orders of magnitude

Mu2e Collaboration

More than 200 scientists from 38 institutions: