Probing charged lepton flavor violation with the Mu2e experiment

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Helmholtz-Zentrum Dresden-Rossendorf

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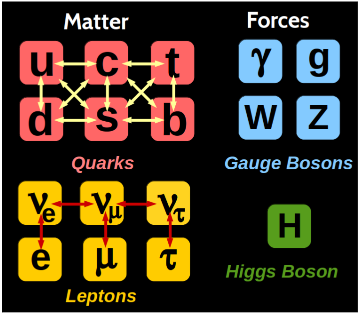
Motivation

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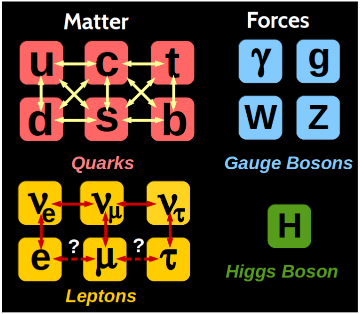
No charged lepton flavor violation (CLFV) observed so far!



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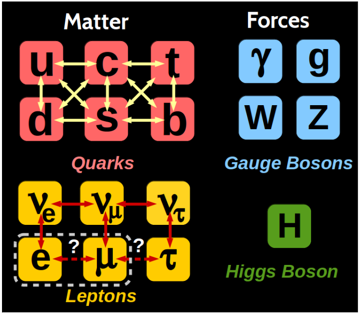


Mu2e will search for the neutrinoless conversion of a muon into an electron in the coulomb field of a nucleus ($\mu N \rightarrow eN$) with a projected

upper limit of 8×10^{-17} (90% CL)

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

New physics

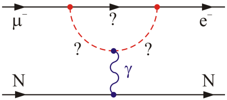
Model independent Lagrangian:

$$L_{CLFV} = \underbrace{\frac{m_\mu}{(\kappa+1)\,\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}}_{\text{“Loop term”}} + \underbrace{\frac{\kappa}{(\kappa+1)\,\Lambda^2}\bar{\mu}_L\gamma_\mu e_L\left(\bar{e}\gamma^\mu e\right)}_{\text{“Contact term”}}$$

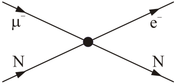
Λ: effective mass scale of New Physics

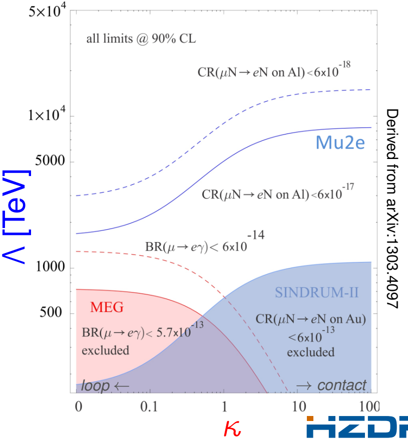
κ: relative contribution of contact term

Loop term: dominates for $\kappa \ll 1$



Contact term: dominates for $\kappa \gg 1$





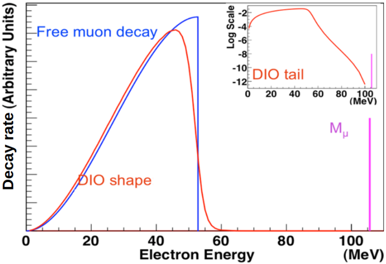
Mu2e will probe $\Lambda \sim O(10^3\text{ -}10^4)$ TeV

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 $\sim$ 900ns in the 1s orbital of the Al nucleus

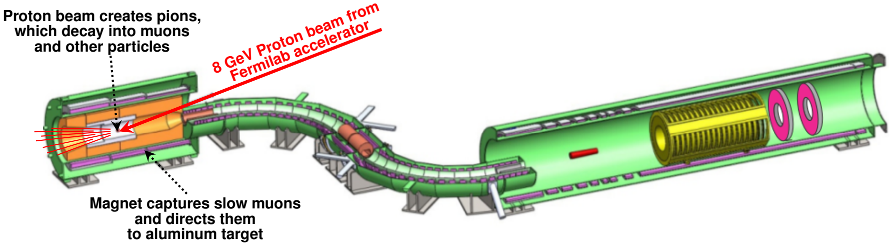
- about 60% of stopped muons undergo the muon capture reaction ($\mu^- + {}^{27}\text{Al} \rightarrow \nu_\mu + {}^{27}\text{Mg}$)
- $\sim$ 40% of stopped muons decay in orbit (DIO)
  - Michel spectrum of decay electrons stops around $M_\mu/2$
- CLFV signal for $\mu \rightarrow e$ conversion gives single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



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

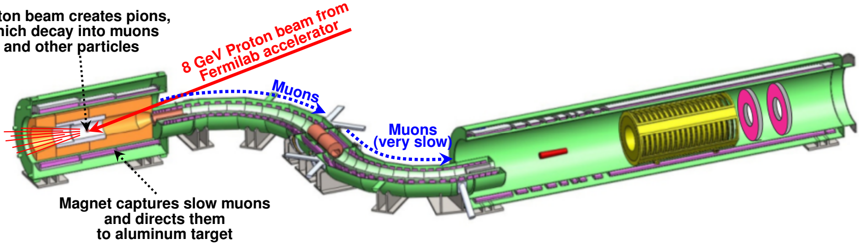
HZDR

The Mu2e experiment



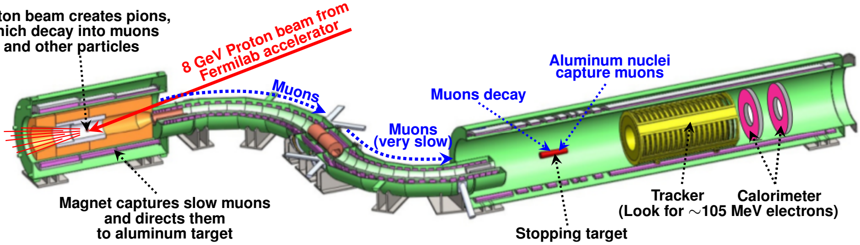
- Muons are produced by 8 GeV proton beam on tungsten target
  - time-averaged beam power: 7.3kW
  - 4×10^7 protons/pulse, pulse separation: 1.695μs
  - Magnetic field in Production Solenoid guides produced pions towards Transport Solenoid
  - Pions decay into muons

The Mu2e experiment



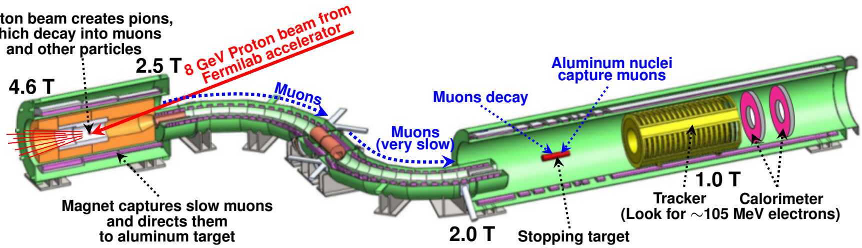
- Muons are transported in s-shaped Transport Solenoid
  - Absorber foils remove antiprotons
  - Solenoidal magnetic fields separate oppositely charged particles
  - Collimators select low-momentum negatively-charged muons.

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

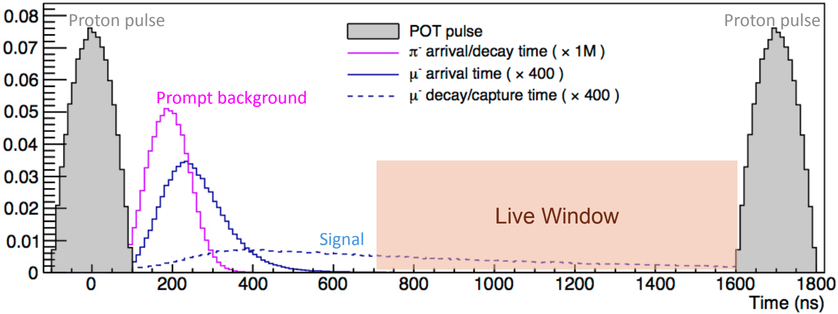
The Mu2e experiment



- Graded fields in the 3 solenoid systems are important
  - to increase muon yields
  - to suppress backgrounds
  - to improve geometric acceptance for signal electrons

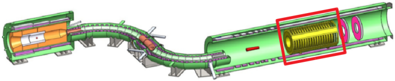
The Mu2e experiment

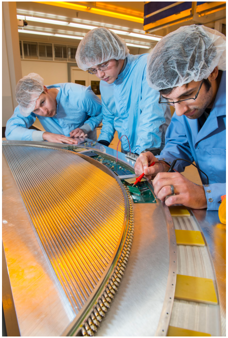
Pulsed proton beam allows definition of a “Live Window” for the signal to suppress prompt background (1695 ns peak-to-peak):



- 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) $\leq 10^{-10}$

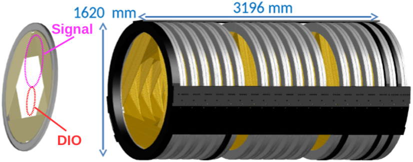
Straw drift tube tracker



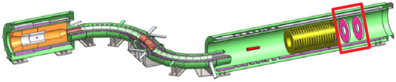


- low mass straw drift tubes (5mm diam.)
- $>$ 20 000 straws
- in vacuum and at $\sim$1 T magn. field
- momentum resolution $\sigma_p < 180$ keV/c

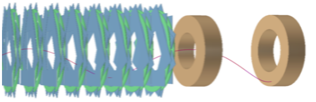
- inner 38 cm not instrumented
  $\rightarrow$ "blind" to low-momenta DIO electrons



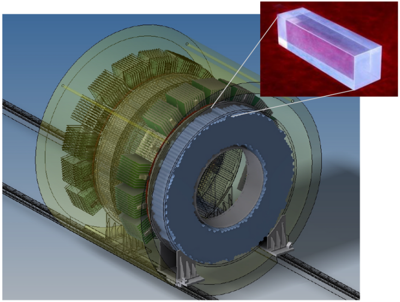
Calorimeter



- composed of two rings separated by half a wavelength of electron trajectory helix

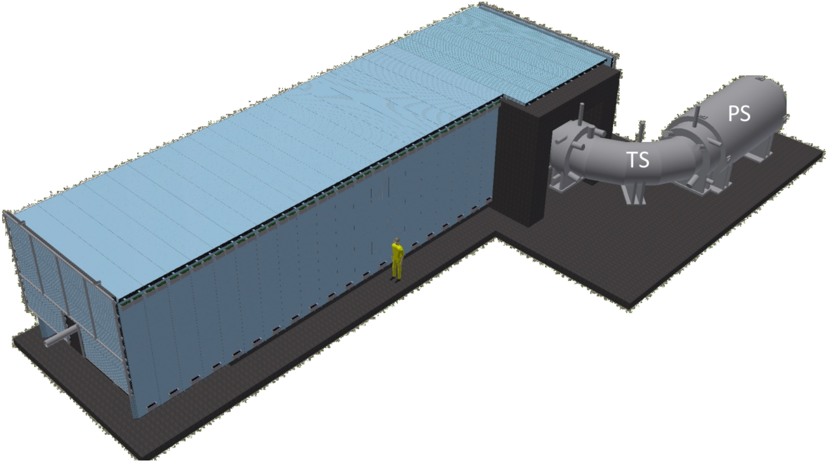


- each ring composed of ~700 pure CsI crystals read out by SiPMs
- independent measurement of
  - energy ($\sigma_E/E \sim 5\%$)
  - time ($\sigma_t \sim 0.5$ns)
  - position ($\sigma_{Pos} \sim 1$cm)
- independent trigger information
- particle ID



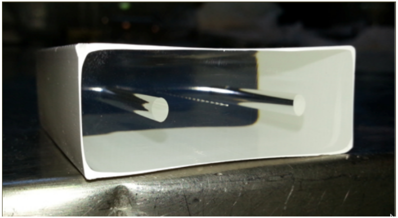
The cosmic ray veto detector

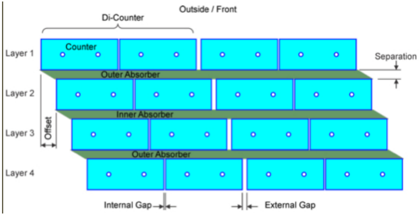
The cosmic ray veto system (CRV) covers entire Detector solenoid and half of the Transportation Solenoid



The cosmic ray veto detector

Without CRV, $\sim$ 1 cosmic-ray induced background event per day

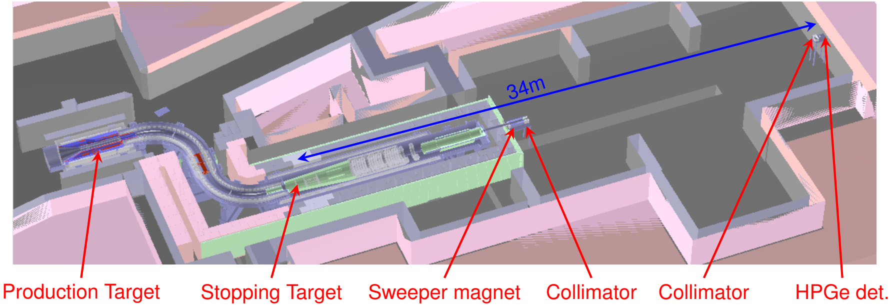




- 4 overlapping layers of scintillator bars ($5 \times 2 \times \sim 450$ cm^3)
- 2 wavelength-shifting fibers/bar
- Read out both end of each fiber with SiPMs
- $\epsilon > 99.4\%$ (per layer) achieved in test beam

The Stopping-Target Monitor

High-purity Germanium (HPGe) detector to determine overall muon-capture rate on Al to about the 10% level

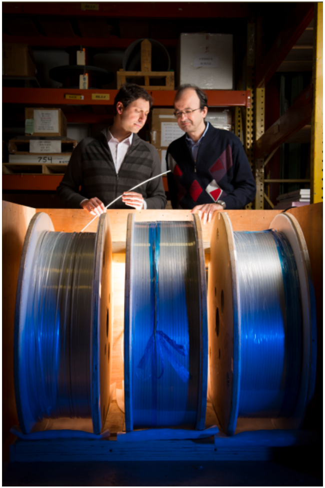


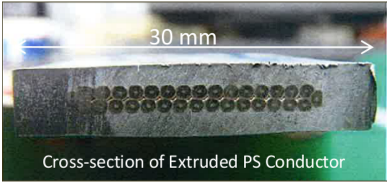
- measures X- and γ-rays from muonic Aluminum
  - 347 keV 2p-1s X-ray (80% of muon stops)
  - 844 keV delayed γ-ray (5% of muon stops)
  - 1809 keV γ-ray (30% of muon stops)
- line-of-sight view of Muon Stopping Target
- sweeper magnet to reduce charged particle background and radiation damage to detector

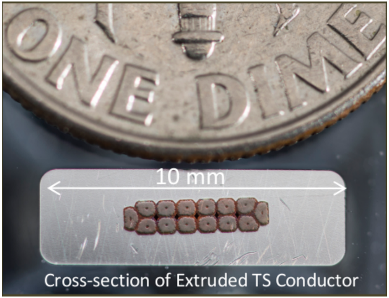
HZDR

Magnet production

In total 75 km of conductor:



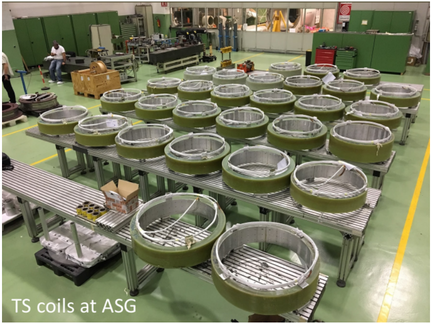




- Conductor production is complete

Magnet production

Transport solenoid production at ASG (Genova) and Fermilab:

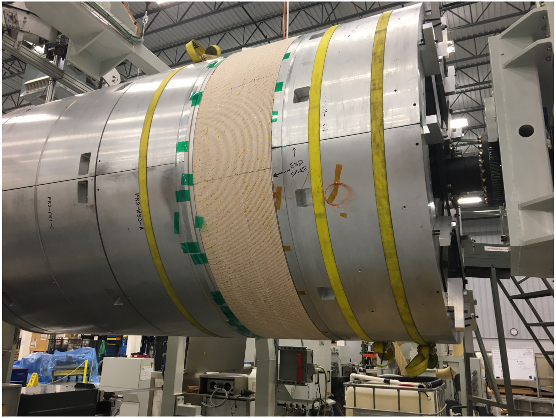


- First TS module at Fermilab undergoing cold test
- All coils have been wound

Magnet production

Production and Detector Solenoid production at General Atomics (Tupelo):

- First demonstration coil with two layers of 70 turns each was successfully completed

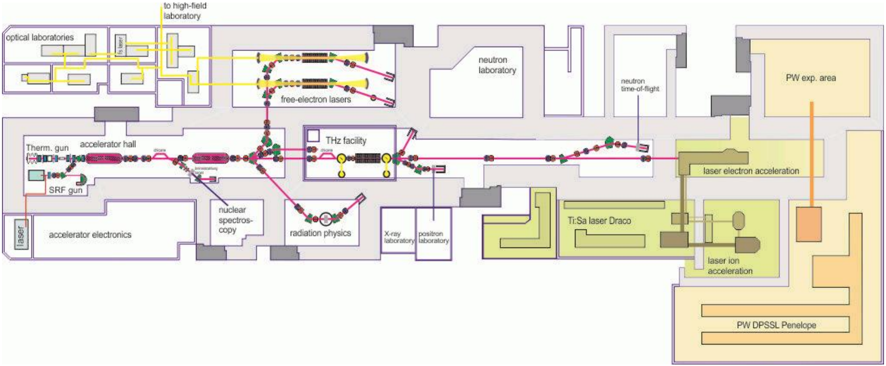


HZDR

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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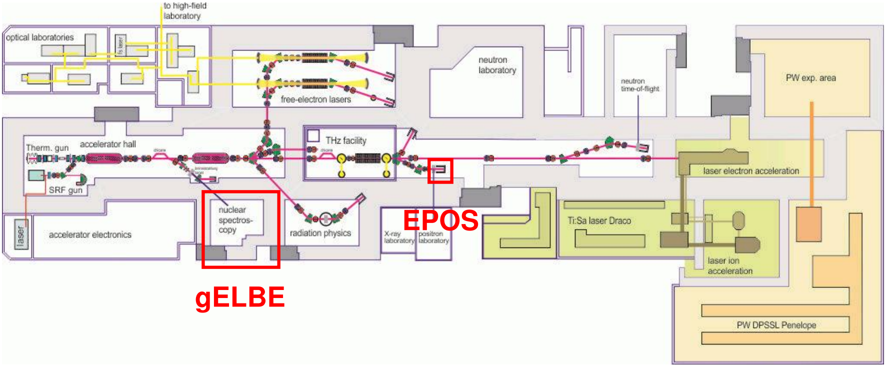


EPOS: Positron (+ Photoneutron) source (Radiation hardness tests)
gELBE: Gamma beam facility (HPGe detector design for STM and calorimeter board testing)

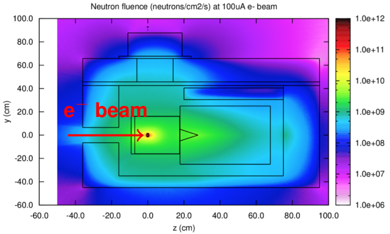
HZDR

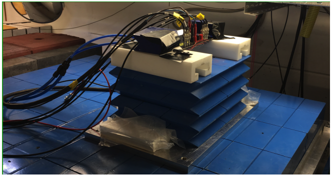
Testing radiation hardness of SiPMs at EPOS

Positron production by ELBE 30 MeV electron beam on tungsten target is accompanied by a large amount of photoproduced neutrons with an energy spectrum which peaks at $\sim$1 MeV.

$\rightarrow$ this matches the expected radiation conditions at Mu2e

- expected neutron fluence has been simulated using FLUKA
- SiPMs from 3 suppliers have been installed on top of the EPOS target bunker for a parasitic beamtime
- dark current of SiPMs has been monitored (stabilized at 20°C)
- integrated fluence of more than 8×10^{11} 1-MeV-equiv. neutrons/cm^2 has been accumulated
- Routinely parasitic irradiation of SiPMs





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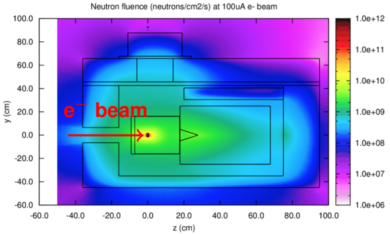
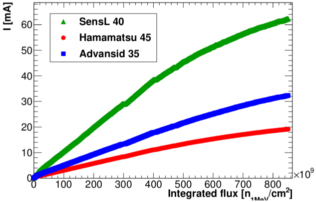
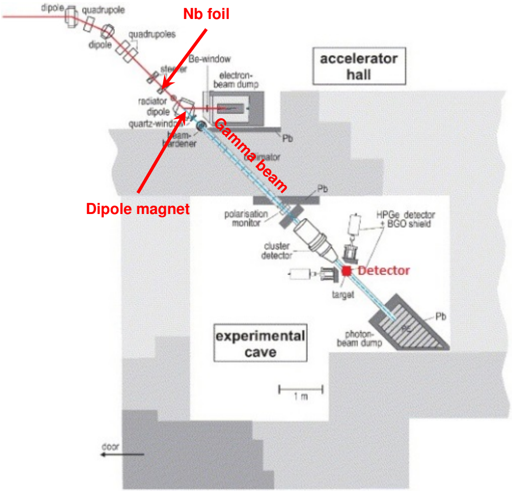




Cordelli et al.
JINST 13 (2018)
T003005

Studying HPGe detector response at gELBE

The gELBE bremsstrahlung facility was used to study HPGe detector performance. gELBE utilizes Bremsstrahlung production from an electron beam impinging on niobium radiator foils.

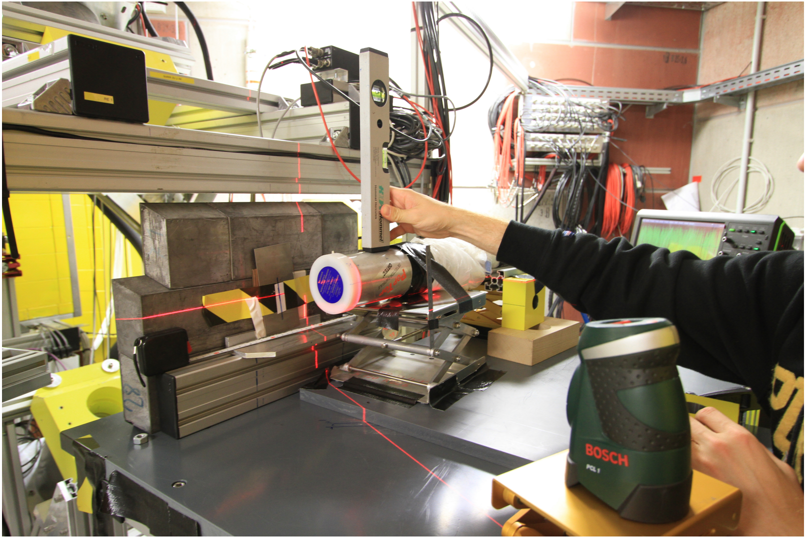


Studying HPGe detector response at gELBE

gELBE delivers a pulsed γ-beam with max. energy of 15 MeV.

- Up to 125kHz of gamma rates expected for Mu2e Stopping-Target Monitor HPGe detector during beam pulse
  - high average γ energy ($\sim$ 5 MeV)
  - high beam pulse occupancy ($\sim$ 20%)
- gELBE pulse separation of 2.4μs close to Mu2e's 1.7μs proton pulse separation
- Goals of the beamtime:
  - Measure HPGe detector performance in the gELBE beam (energy resolution, radiation damage,...)
  - Understand best beam and detector geometry and position (including absorbers)
- HZDR provides radiation transport simulations using the FLUKA code to estimate γ energy spectrum, energy deposit in crystal etc.
- Detector specifications have been finalized and order has been placed

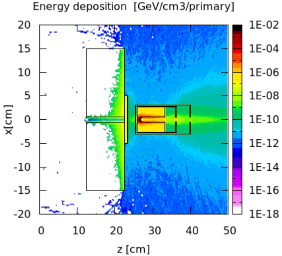
Studying HPGe detector response at gELBE



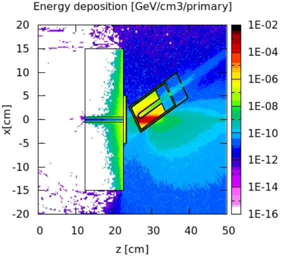
Studying HPGe detector response at gELBE

Studying energy deposition in crystal:

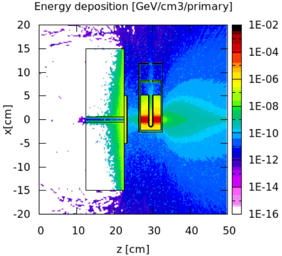
- Simulate gELBE bremsstrahlung spectrum starting from electron beam hitting niobium foil and propagate it till HPGe detector position
- HPGe detector behind lead wall with $1 cm^2$ collimator hole and copper/aluminum absorber plates to shield from lead fluorescence.



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



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



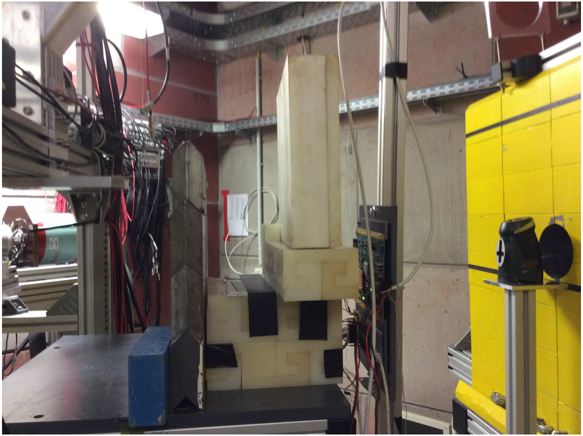
Average energy deposition (1759.4 ± 0.08) keV per primary γ

HZDR

Irradiation of calorimeter digitizer board at gELBE

Digitizer board behind lead and PE collimator walls to allow individual irradiation of board components

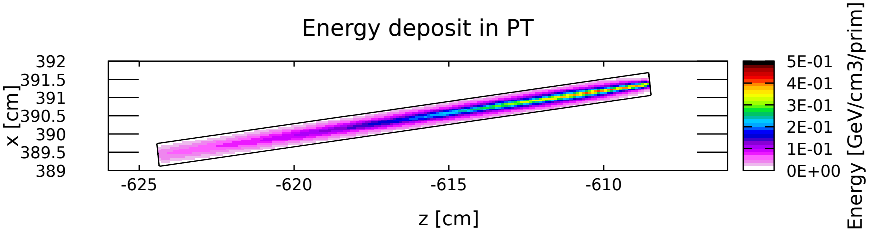
- Gamma radiation produced by 15 MeV electron beam with 700 μA on niobium radiator



HZDR

Mu2e MC simulation with FLUKA

Mu2e Production Target modeled with the FLUKA radiation transport software



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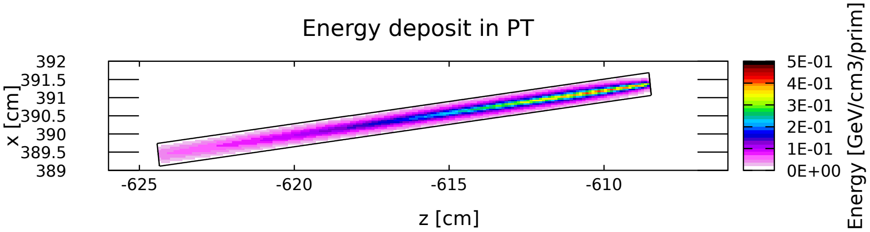

FLUKA finds an average energy deposition of **0.833 GeV/proton** $\pm$ **0.2%**, which corresponds to **730 Watt@7.3kW beam power**.

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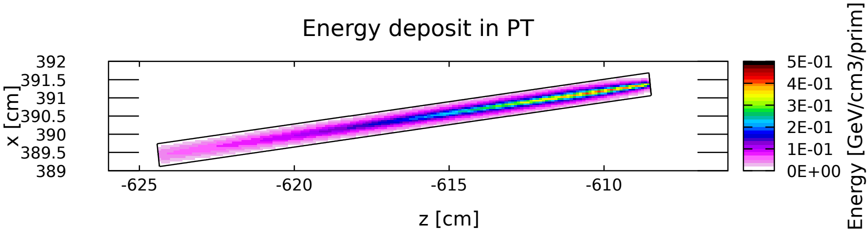

FLUKA finds an average energy deposition of **0.833 GeV/proton** $\pm$ **0.2%**, which corresponds to **730 Watt@7.3kW beam power**.

In good agreement with the results obtained with other Monte Carlo codes:

> **703 Watt@7.3kW beam power (G4Beamline)**
>
> **713 Watt@7.3kW beam power (MARS)**

Conclusion & Outlook

- The Mu2e experiment at FERMILAB will search for the neutrinoless conversion of a muon into an electron in the coulomb field of an Aluminum nucleus
  - projected upper limit: 8×10^{-17} (90% CL)
- Detector design ready, construction started
- Solenoid design ready, coil fabrication started
- HZDR contributes with beamtimes at the ELBE radiation source for tests of radiation hardness of calorimeter components and HPGe detector design for STM
- In addition studies of production and stopping target with FLUKA MC simulation code are under way
  - implement more of the geometry
  - include magnetic field
- With physics datataking starting in 2023, 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: