

# Probing charged lepton flavor violation with the Mu2e experiment

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*Helmholtz-Zentrum Dresden-Rossendorf*

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DRESDEN  
concept



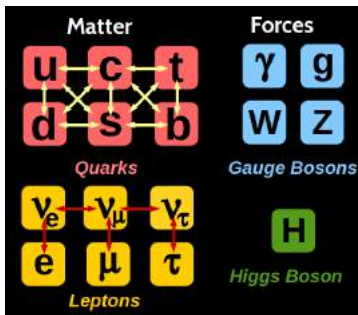
**HZDR**

HELMHOLTZ  
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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

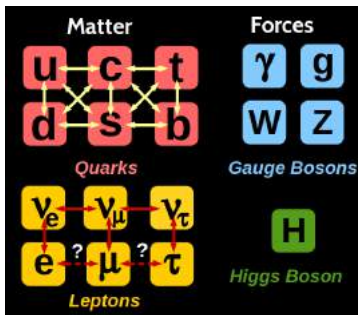


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No charged lepton flavor violation (CLFV) observed so far!

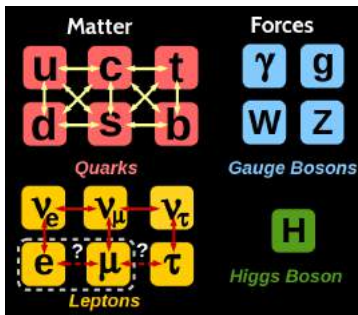


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**Mu2e** will search for the neutrinoless conversion of a muon into an electron in the coulomb field of a nucleus ( $\mu N \rightarrow e N$ ) with a projected

**upper limit of  $8 \times 10^{-17}$  (90% CL)**

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

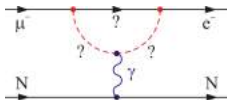
Model independent Lagrangian:

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

$\Lambda$ : effective mass scale of New Physics

$\kappa$ : relative contribution of contact term

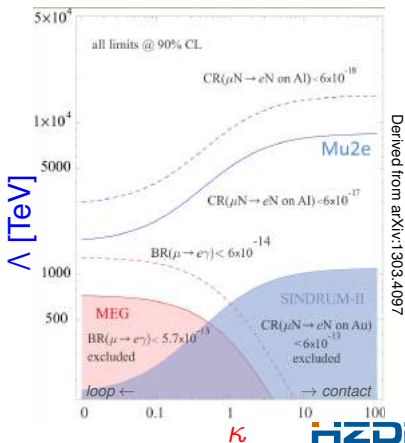
Loop term: dominates for  $\kappa \ll 1$



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



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

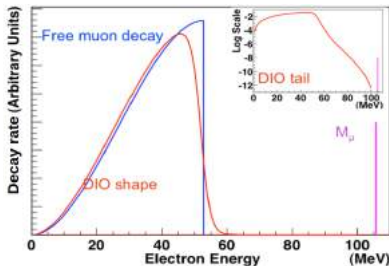


# The Mu2e experiment

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

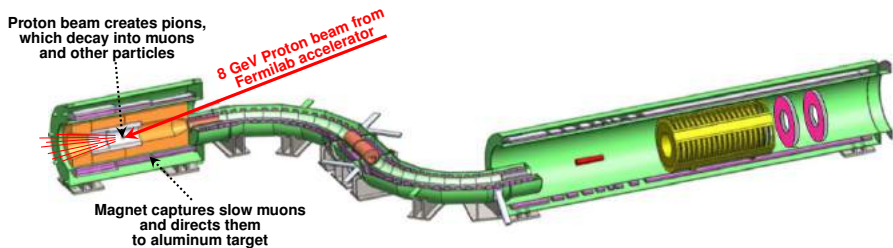
Stopped muons have a lifetime of  $\sim 900\text{ns}$  in the 1s orbital of the Al nucleus

- 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
  - $E_e = 104.973 \text{ MeV} \simeq M_\mu$



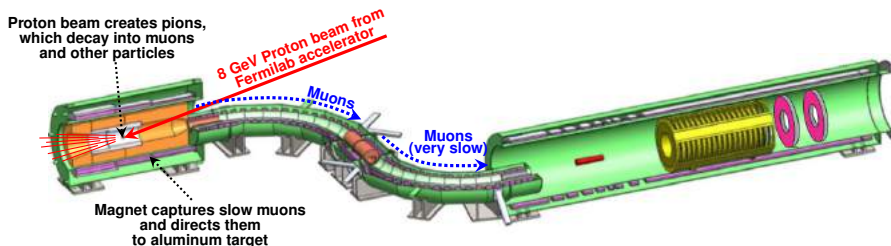
$$\text{Normalized ratio } R_{\mu e} = \frac{N(\mu^- + \text{Al} \rightarrow e^- + \text{Al})}{N(\mu^- + \text{Al} \rightarrow \text{nuclear capture})}$$

# The Mu2e experiment



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

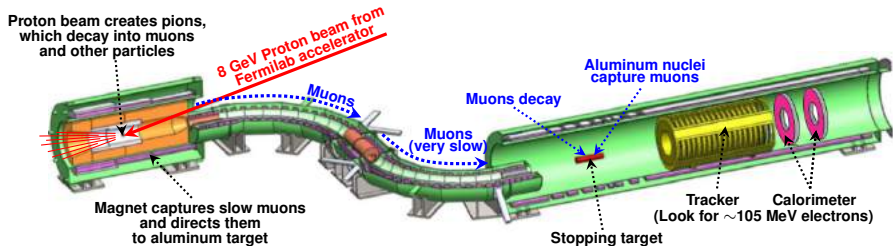
# The Mu2e experiment



- 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.

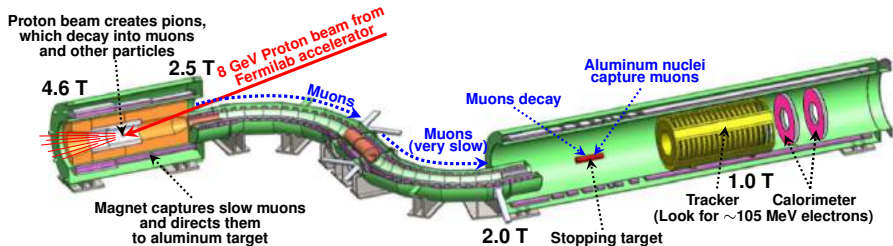


# The Mu2e experiment



- 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

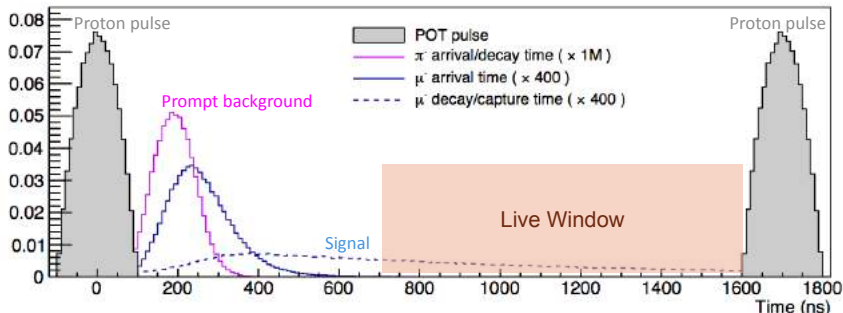
# The Mu2e experiment



- 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):



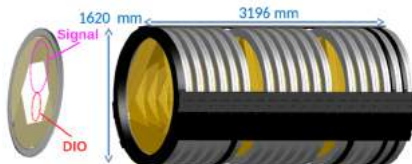
- Fermilab accelerator complex provides optimal pulse spacing for Mu2e
- 700 ns delay allows to suppress prompt background from pions by  $\sim 10^{-11}$
- Must achieve extinction  $(N_{p^+ \text{ out of bunch}})/(N_{p^+ \text{ in bunch}}) \leq 10^{-10}$

# Straw drift tube tracker



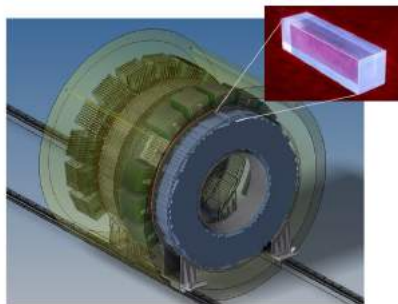
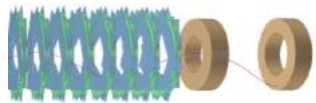
- low mass straw drift tubes (5mm diam.)
- > 20 000 straws
- in vacuum and at  $\sim 1$  T magn. field
- momentum resolution  $\sigma_p < 180$  keV/c

- inner 38 cm not instrumented  
→ “blind” to low-momenta DIO electrons



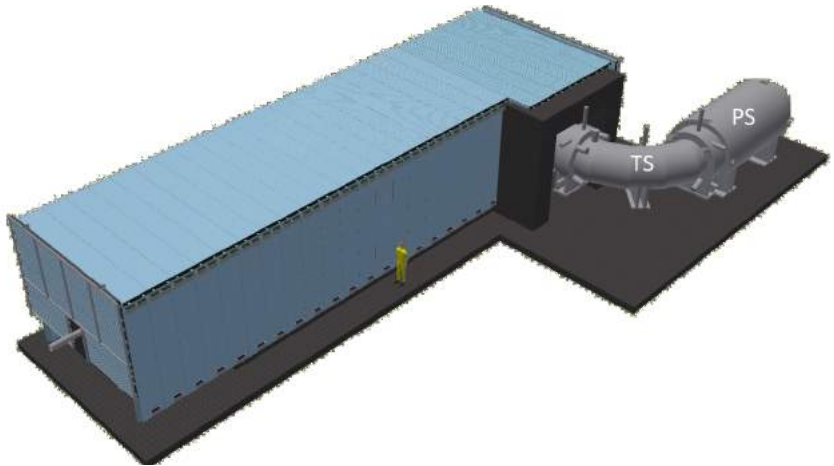
# Calorimeter

- composed of two rings separated by half a wavelength of electron trajectory helix
- each ring composed of  $\sim 700$  pure CsI crystals read out by SiPMs
- independent measurement of
  - energy ( $\sigma_E/E \sim 5\%$ )
  - time ( $\sigma_t \sim 0.5\text{ns}$ )
  - position ( $\sigma_{\text{Pos}} \sim 1\text{cm}$ )
- independent trigger information
- particle ID



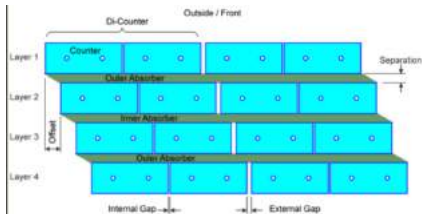
# The cosmic ray veto detector

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



# The cosmic ray veto detector

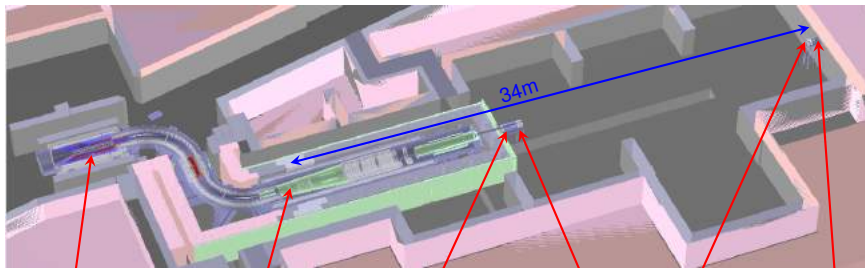
Without CRV,  $\sim 1$  cosmic-ray induced background event per day



- 4 overlapping layers of scintillator bars ( $5 \times 2 \times \sim 450 \text{ cm}^3$ )
- 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



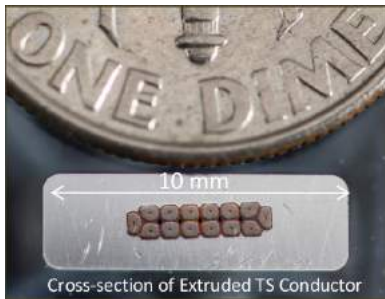
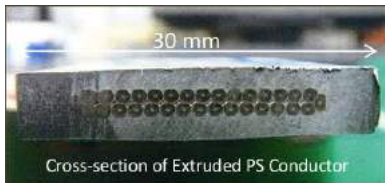
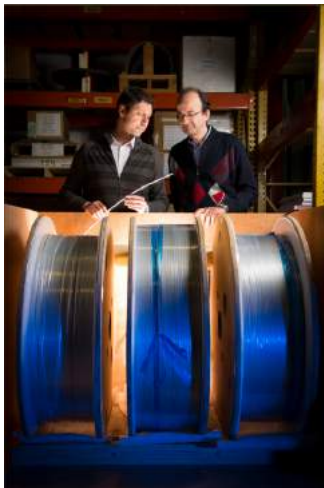
Production Target    Stopping Target    Sweeper magnet    Collimator    Collimator    HPGe det.

- measures X- and  $\gamma$ -rays from muonic Aluminum
  - 347 keV 2p-1s X-ray (80% of muon stops)
  - 844 keV delayed  $\gamma$ -ray (5% of muon stops)
  - 1809 keV  $\gamma$ -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



# 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):

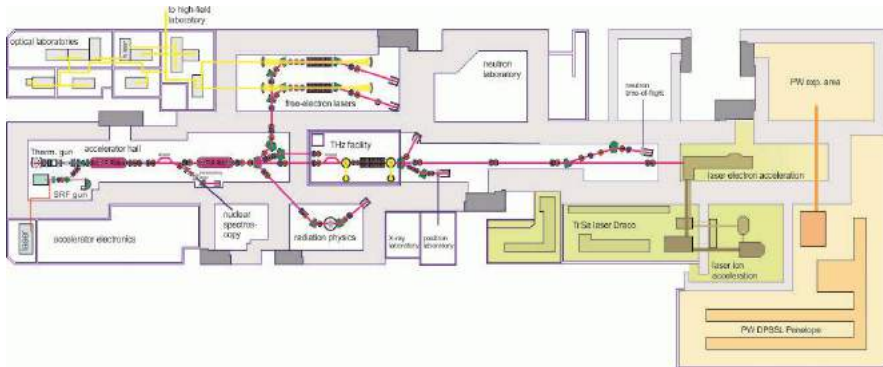
- First demonstration coil with two layers of 70 turns each was successfully completed



# Mu2e@HZDR: The ELBE radiation source

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

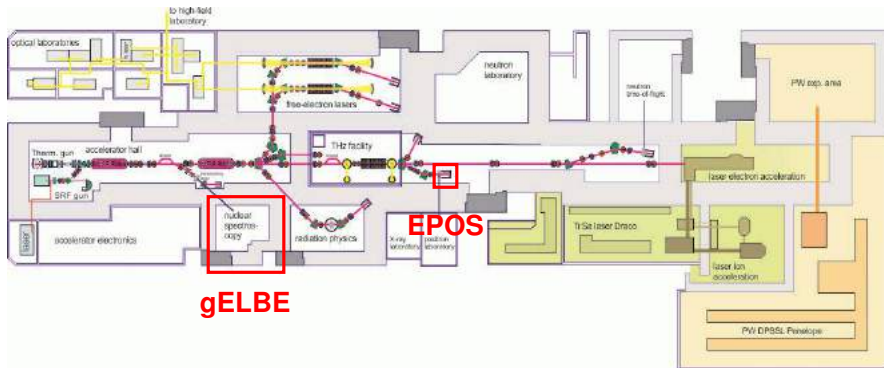
- $E_e \leq 40$  MeV;  $I_e \leq 1$  mA; Micropulse duration  $10 \text{ ps} < \Delta t < 1 \text{ }\mu\text{s}$



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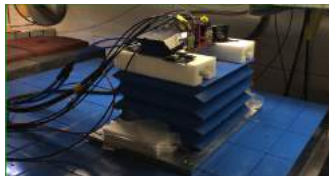
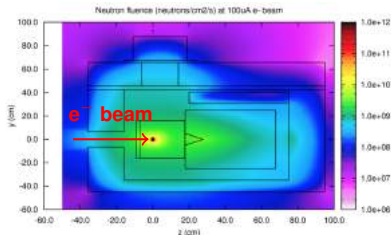
**EPOS:** Positron (+ Photoneutron) source (Radiation hardness tests)  
**gELBE:** Gamma beam facility (HPGe detector design for STM and calorimeter board testing)

# 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.

→ 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  $20^{\circ}\text{C}$ )
- integrated fluence of more than  $8 \times 10^{11}$  1-MeV-equiv. neutrons/cm<sup>2</sup> has been accumulated
- Routinely parasitic irradiation of SiPMs

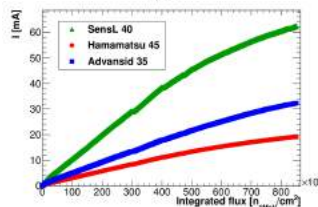
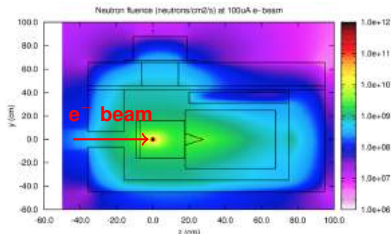


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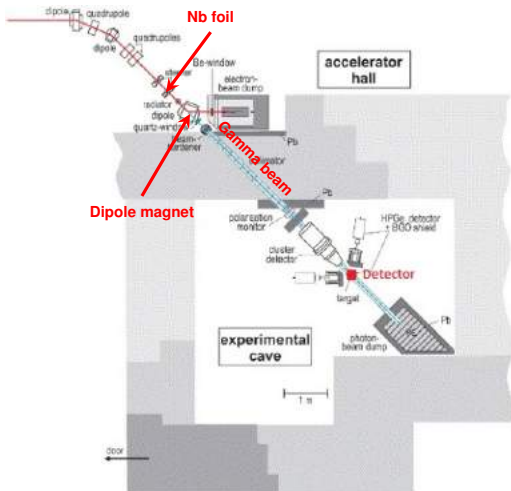
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Cordelli et al.  
JINST 13 (2018)  
T003005

# 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.



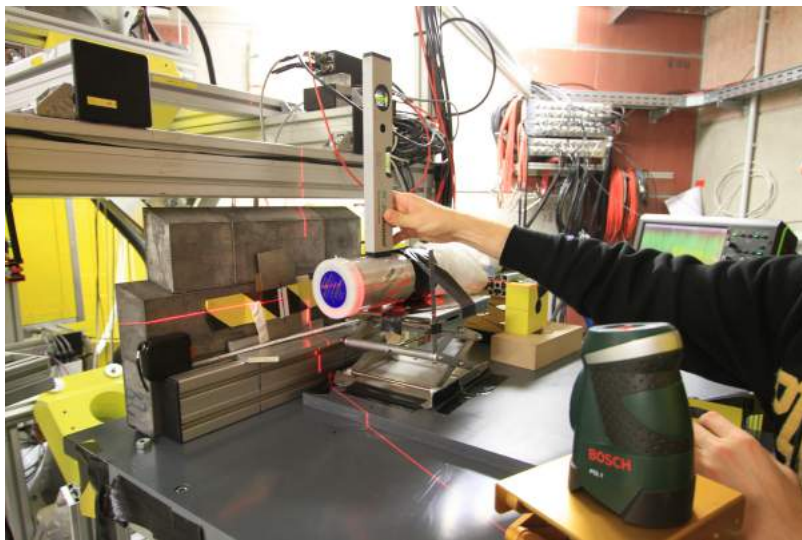


# Studying HPGe detector response at gELBE

gELBE delivers a pulsed  $\gamma$ -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  $\gamma$  energy ( $\sim 5$  MeV)
  - high beam pulse occupancy ( $\sim 20\%$ )
- gELBE pulse separation of  $2.4\mu\text{s}$  close to **Mu2e**'s  $1.7\mu\text{s}$  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  $\gamma$  energy spectrum, energy deposit in crystal etc.
- Detector specifications have been finalized and order has been placed

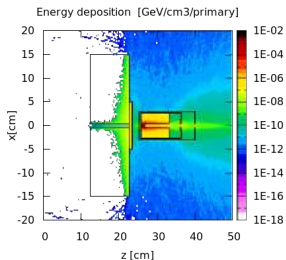
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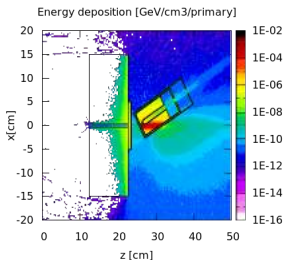
# Studying HPGe detector response at gELBE

Studying energy deposition in crystal:

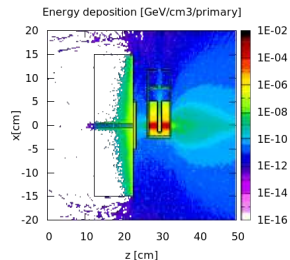
- Simulate gELBE bremsstrahlung spectrum starting from electron beam hitting niobium foil and propagate it till HPGe detector position
- HPGe detector behind lead wall with  $1\text{cm}^2$  collimator hole and copper/aluminum absorber plates to shield from lead fluorescence.



Average energy deposition  
( $508.68 \pm 0.11$ ) keV  
per primary  $\gamma$



Average energy deposition  
( $1846.3 \pm 0.16$ ) keV  
per primary  $\gamma$

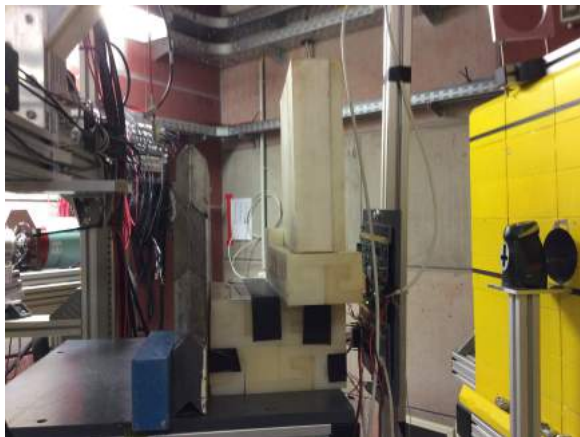


Average energy deposition  
( $1759.4 \pm 0.08$ ) keV  
per primary  $\gamma$

# Irradiation of calorimeter digitizer board at gELBE

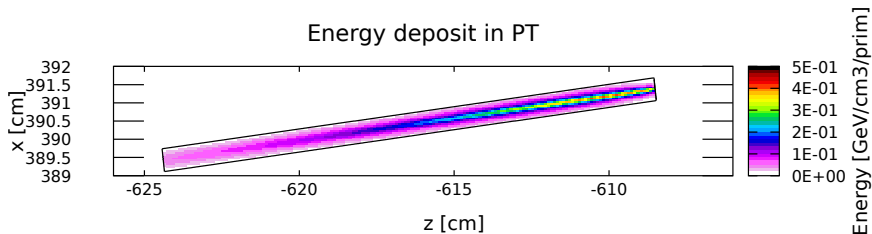
Digitizer board behind lead and PE collimator walls to allow individual irradiation of board components

- Gamma radiation produced by 15 MeV electron beam with 700  $\mu\text{A}$  on niobium radiator



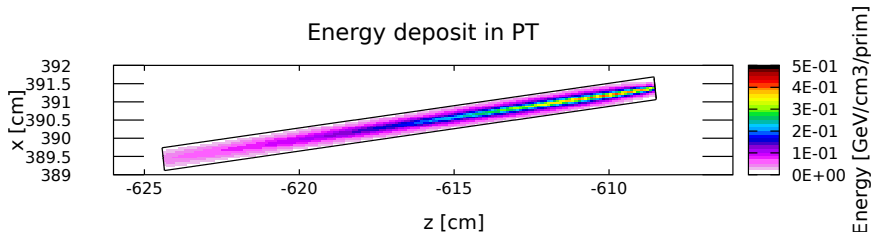
# Mu2e MC simulation with FLUKA

Mu2e Production Target modeled with the FLUKA radiation transport software



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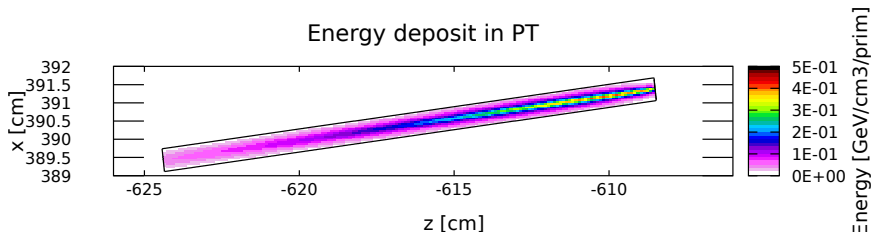
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FLUKA finds an average energy deposition of **0.833 GeV/proton  $\pm$  0.2%**, which corresponds to **730 Watt@7.3kW beam power**.

# Mu2e MC simulation with FLUKA

Mu2e Production Target modeled with the FLUKA radiation transport software



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:  $8 \times 10^{-17}$  (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 data taking starting in 2023, **Mu2e** will either unambiguously discover CLFV or push the limit on muon→electron conversion by four orders of magnitude



# Mu2e Collaboration

More than 200 scientists from 38 institutions:

