Development of the Mu2e STM

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Motivation

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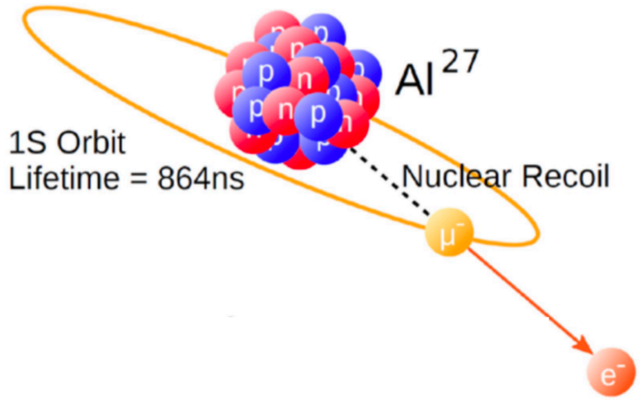
- Search for neutrinoless conversion of muon to electron, in vicinity of a nucleus
- Observation would be a violation of **charged lepton flavour**
- Evidence of physics beyond the SM



$E_e(Al) = M_\mu - E_b - E_{recoil}$
$= 105$ MeV

- Measure ratio of conversions to muon captures:

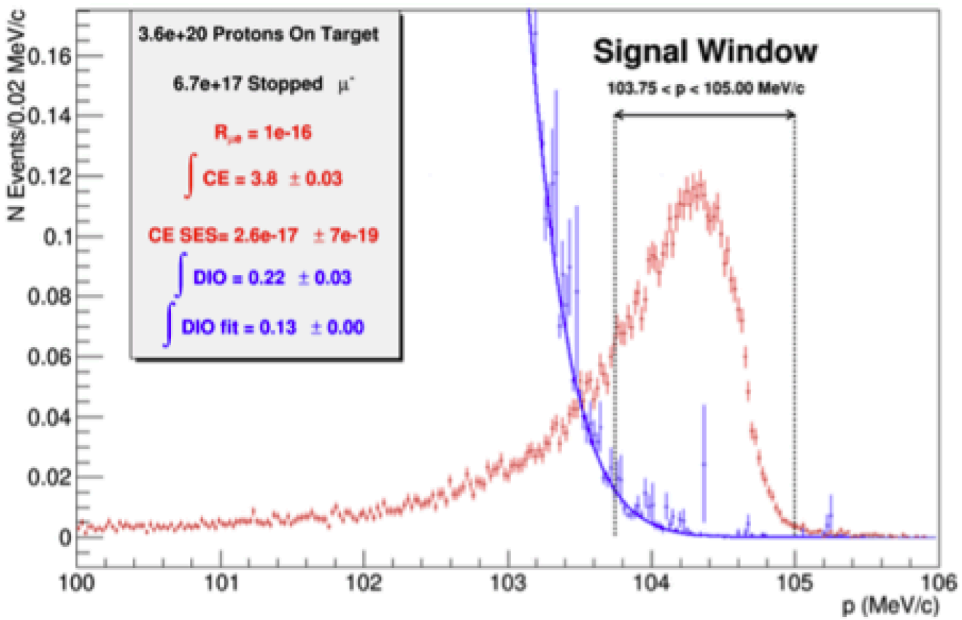
$$R_{\mu e} = \mu^- + A(Z,N) \to e^- + A(Z,N) \,/\, \mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N)$$

- Highly suppressed in SM (rate $<10^{-50}$)
- There is an observable rate in many **new physics** models

Mu2e Concept

- Stop pulsed beam of muons in thin Al foils and form muonic ^{27}Al atoms
- Wait for decays
  - **Normalisation:** 61% undergo muon capture reaction $\mu^- + {}^{27}\mathrm{Al} \rightarrow \nu_\mu + {}^{27}\mathrm{Mg}$
  - **Prompt background:** 39% decay in orbit (muon to electron and 2 neutrinos)
  - **CLFV signal:** $<10^{-12}$ muon to electron conversion (monoenergetic electrons at 105MeV)

Simulation showing DIO background (blue) and CLFV signal (red) for a conversion rate of 10^{-16} and 3 years of running



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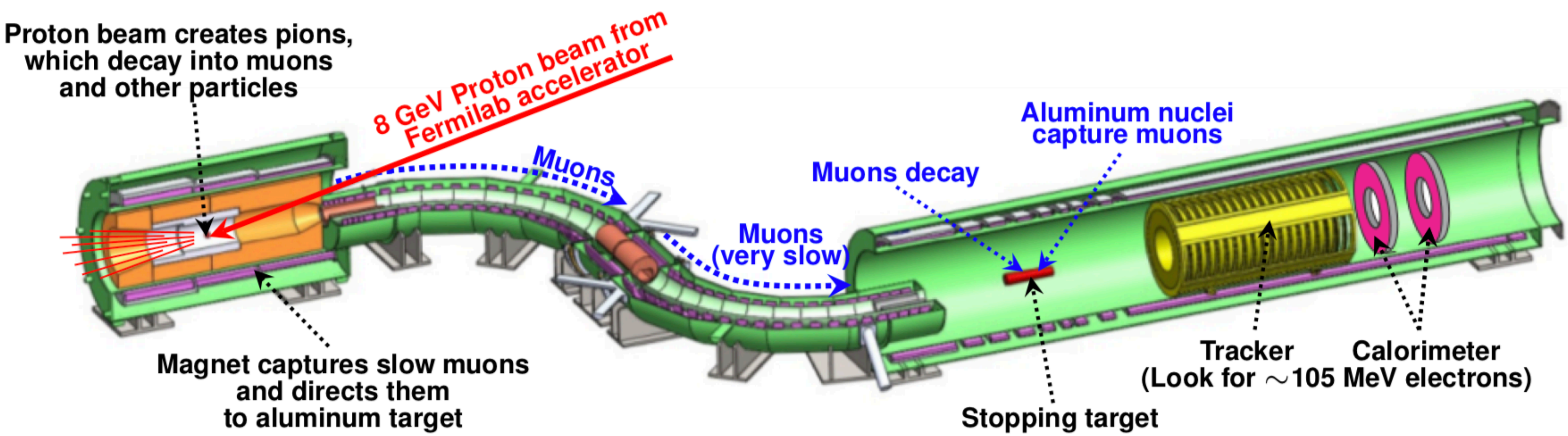
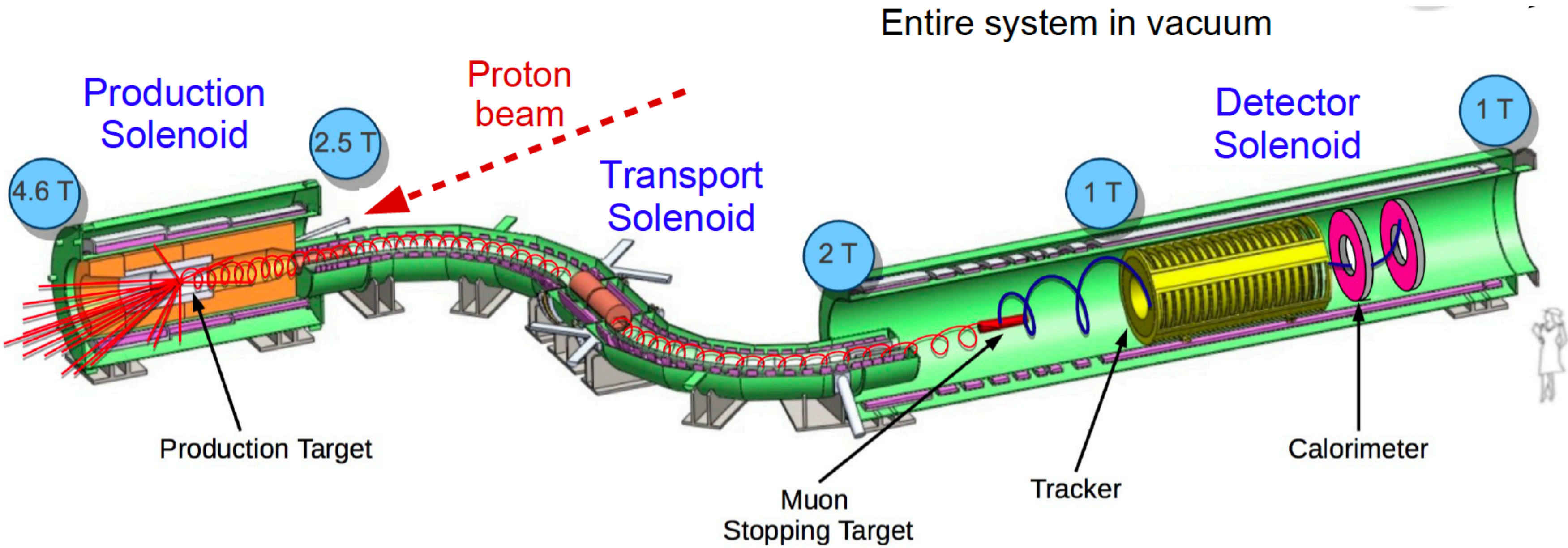
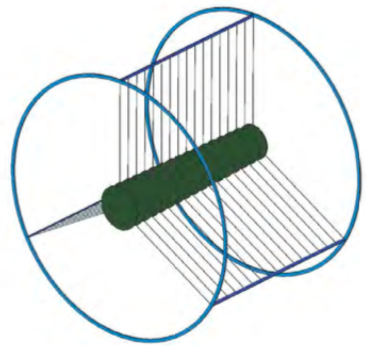


Mu2e Apparatus

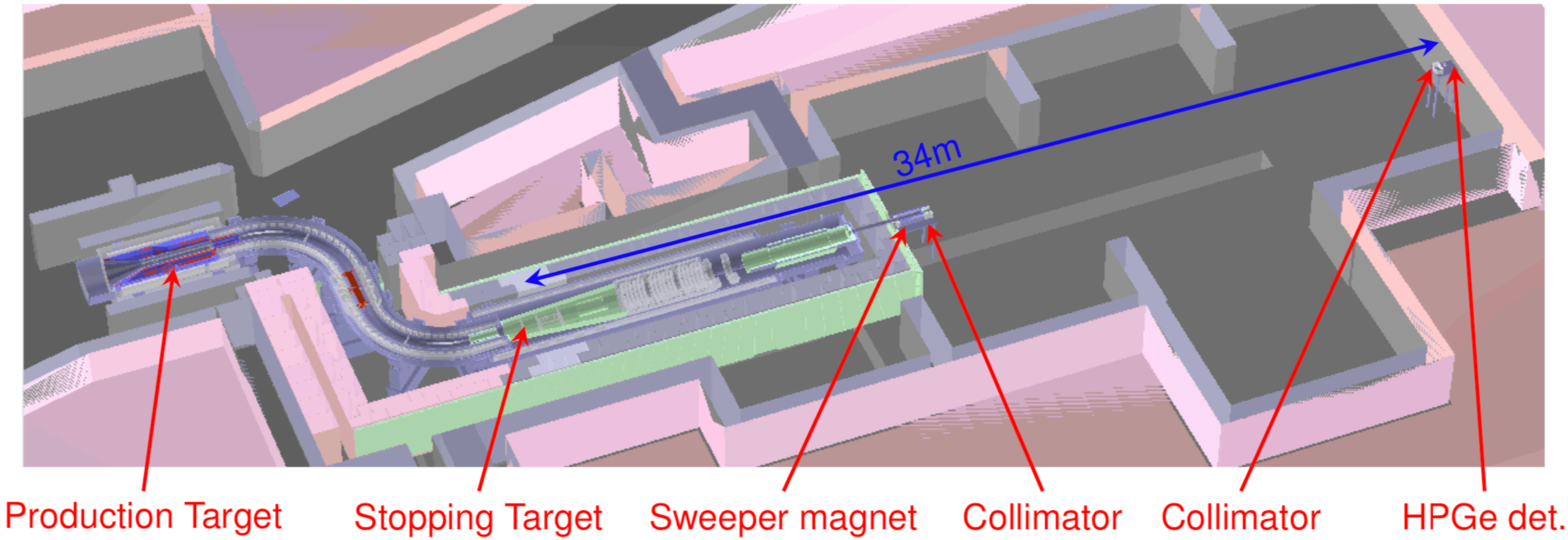


Stopping target:

- Muon stopping target consists of 17 thin aluminium discs along the axis of the detector solenoid
- 10^{10} muons stopped per second in Al target

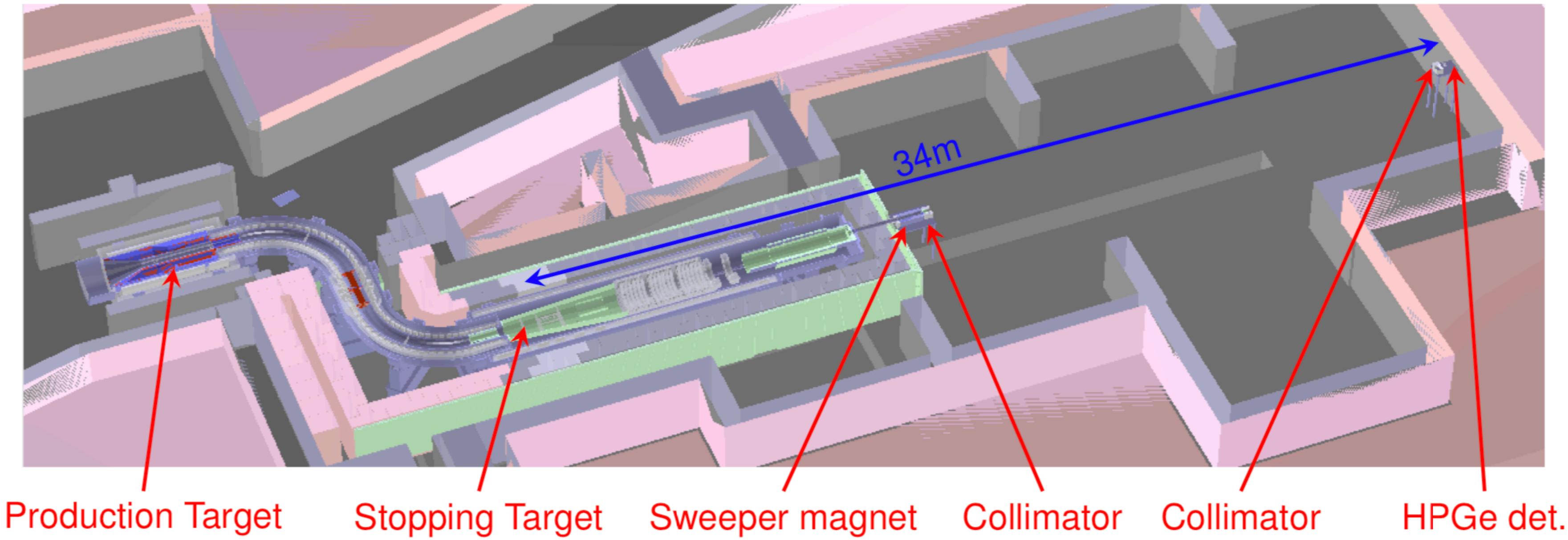


Mu2e STM



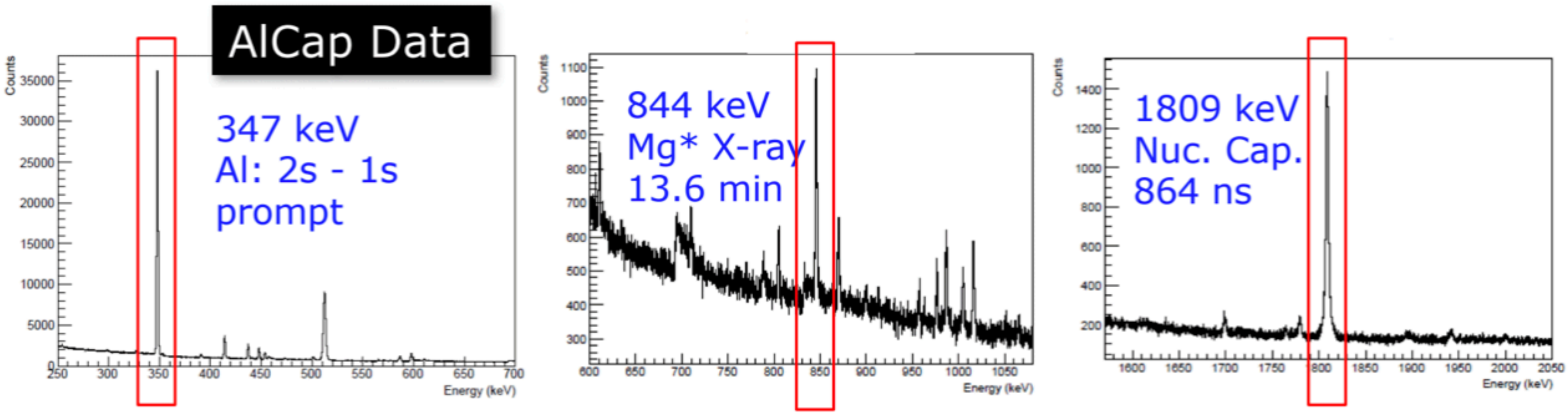
- When muon stops in Al, it quickly (1 fs) cascades to 1s ground state
- Emits X-rays at characteristic energies that can be used to monitor number of stopped muons – aim of the **STM**

Mu2e STM



- STM located 34m from aluminium target (where muons are captured)
- Collimation and a sweeper magnet reduce background rate at the HPGe detector

Mu2e STM



- Need excellent resolution at high rate (90 kHz/cm^2 photons)
- Photons of interest from 347 keV to 1809 keV
- Large bremsstrahlung background, neutrons

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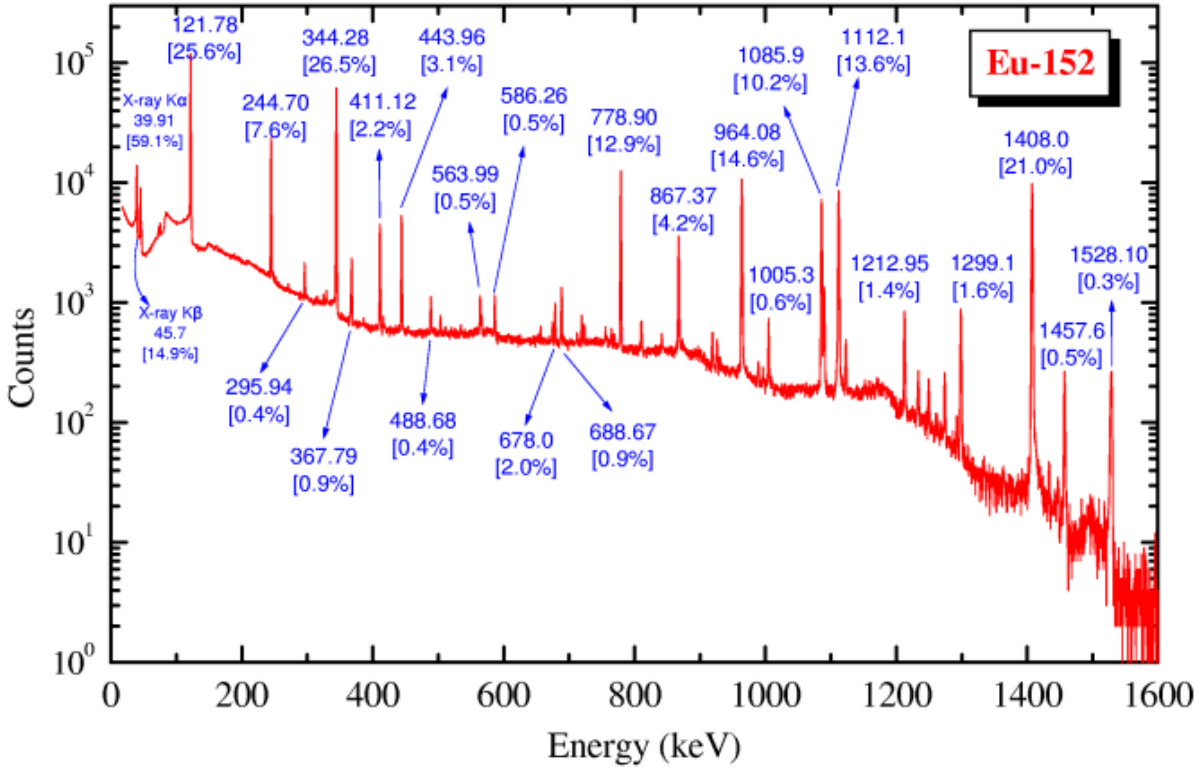
Gamma-ray spectroscopy



- Gamma-ray detectors: **HPGe**, Si(Li), CZT, NaI, BGO, $LaBr_3$
- Detector properties: energy resolution, detection efficiency, time resolution, count-rate capabilities

HPGe detector production

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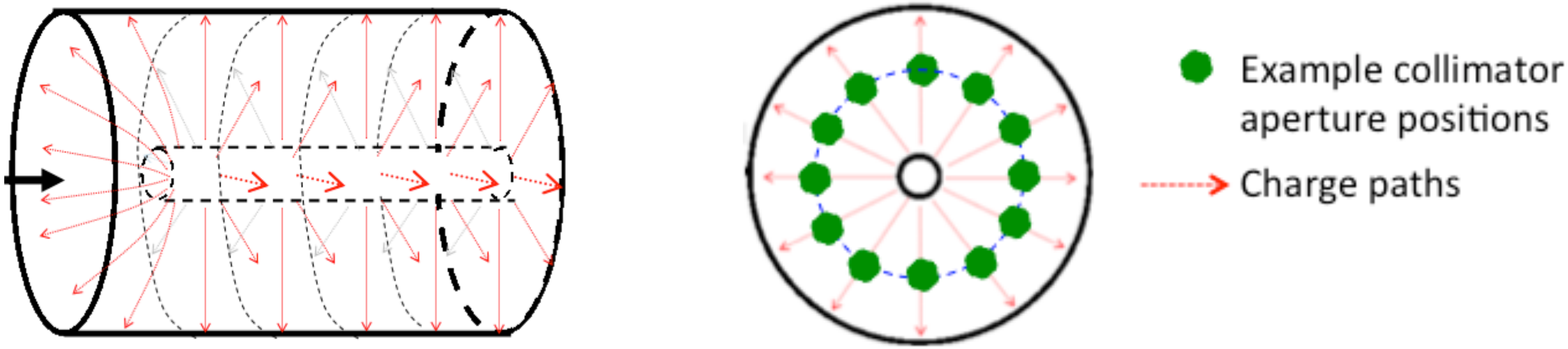
- Detector specifications
- High quality supplier of zone refined germanium
- Cut and shape the crystal with specific crystallographic axis orientation
- Contact the crystal
- Design and build the cryostat
- Select and integrate preamplifier
- Integrate with collimator and DAQ system
- Characterisation

UK team: UoL, UoM, UCL

Manufacturer (Ortec/Ametek)

UK team: UoL, UoM, UCL

HPGe detector design



- **Efficiency and peak-to-total:** Size and shape of crystal, size and location of collimator aperture (energy dependence)
- **Energy resolution:** Size and shape of crystal, signal processing and radiation damage
- **Rate:** size and shape of crystal, size and location of collimator aperture, preamplifier and signal processing

STM challenges

- Incomplete energy collection in the detector (degrading signal to noise)
- High levels of prompt bremsstrahlung radiation (electrons produced at production tungsten transported to the stopping target)
- Radiation damage expected from high neutron flux
- Rates will be high, detector preamplifiers will need to be able to quickly recover, as governed by the pulse structure
- Collimation systems will be required to reduce the rates
- Small footprint available for STM

STM challenges

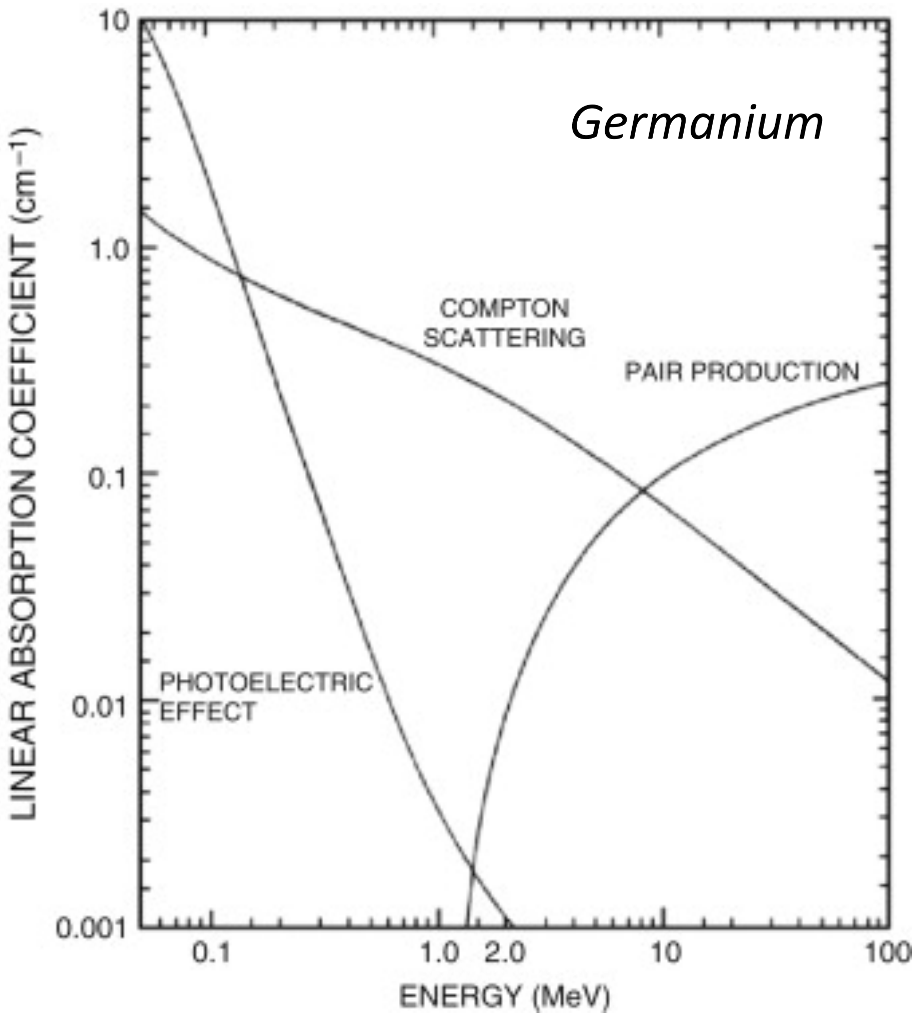
- Gamma-rays that deposit only a fraction of their energy in the detector contribute to background
- Maximise Peak to Compton ratio

$\sigma_{photo} \sim Z^{4\text{-}5}$

$\sigma_{compton} \sim Z$

$\sigma_{pair} \sim Z^2$

Varies as a function of energy!



HPGe detectors

Single HPGe large volume

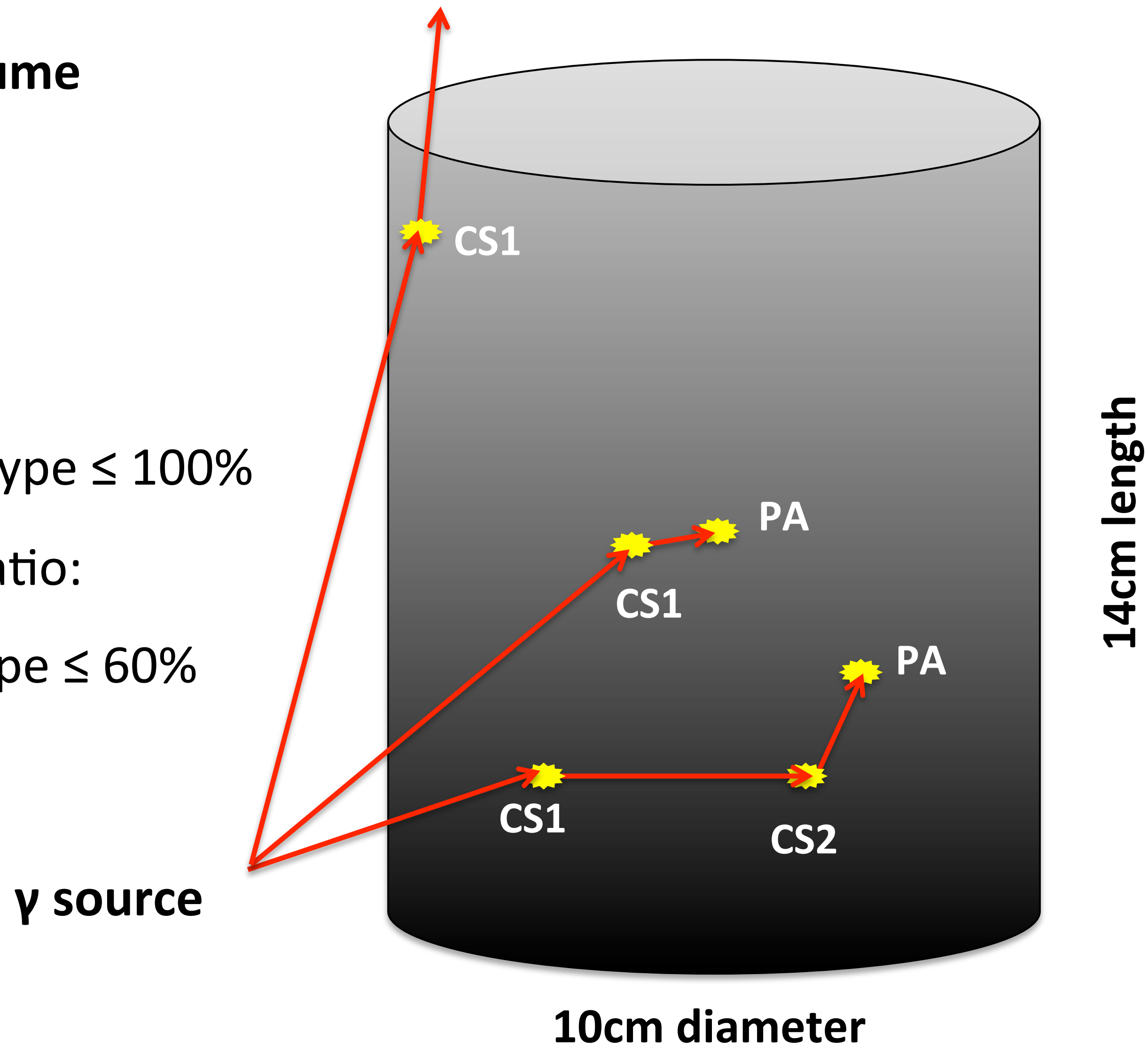
detector performance

- Relative efficiency:

  p-type ≤ 150%, n-type ≤ 100%

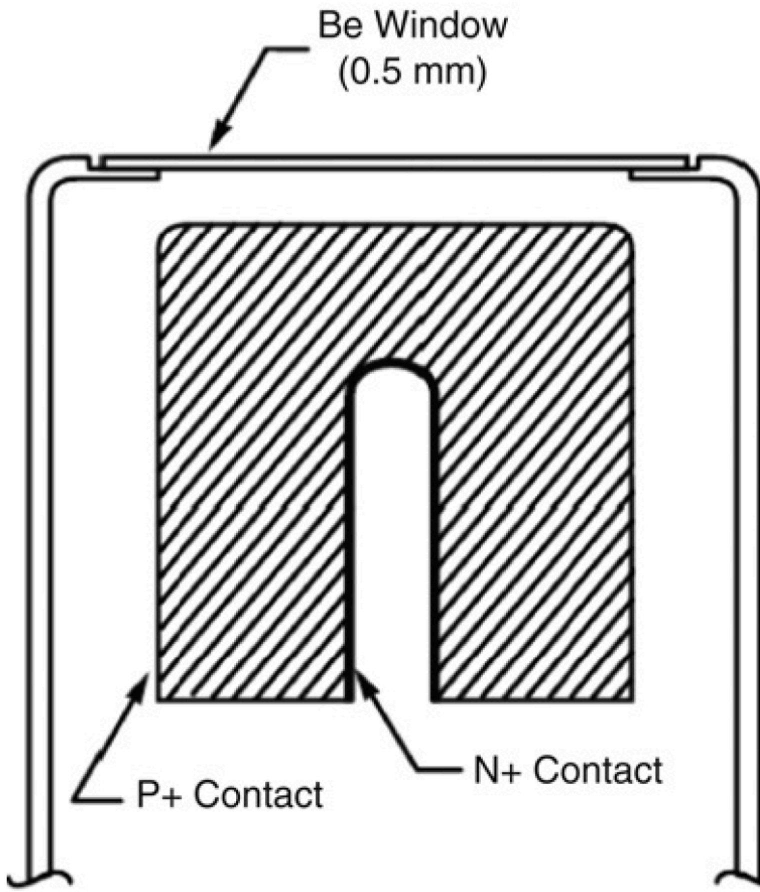
- Peak to Compton ratio:

  p-type ≤ 80%, n-type ≤ 60%



Radiation Damage

- Fast neutrons can dislocate ge atoms from their lattice position
- Hole traps uniformly distributed through crystal
- Most interactions closer to outer contact, so holes have shorter average collection path in n-type than p-type
- p-type an order of magnitude more sensitive to radiation damage
- Degraded energy resolution after ~$2x10^{9}$ ncm^{-2}
- Hole traps can be moved by annealing the detector



n-type: holes collected at outer p+ contact

Radiation Damage

- Germanium crystal annealed for several days at 100-120°C
- Detector heated in cryostat via the cold finger
- Cryostat under vacuum pump to avoid surface contamination
- Crystal temperature can be measured with a PT100 resister at the cold finger
- Cold components of preamp could be damaged by annealing
- Most of detector performance recoverable

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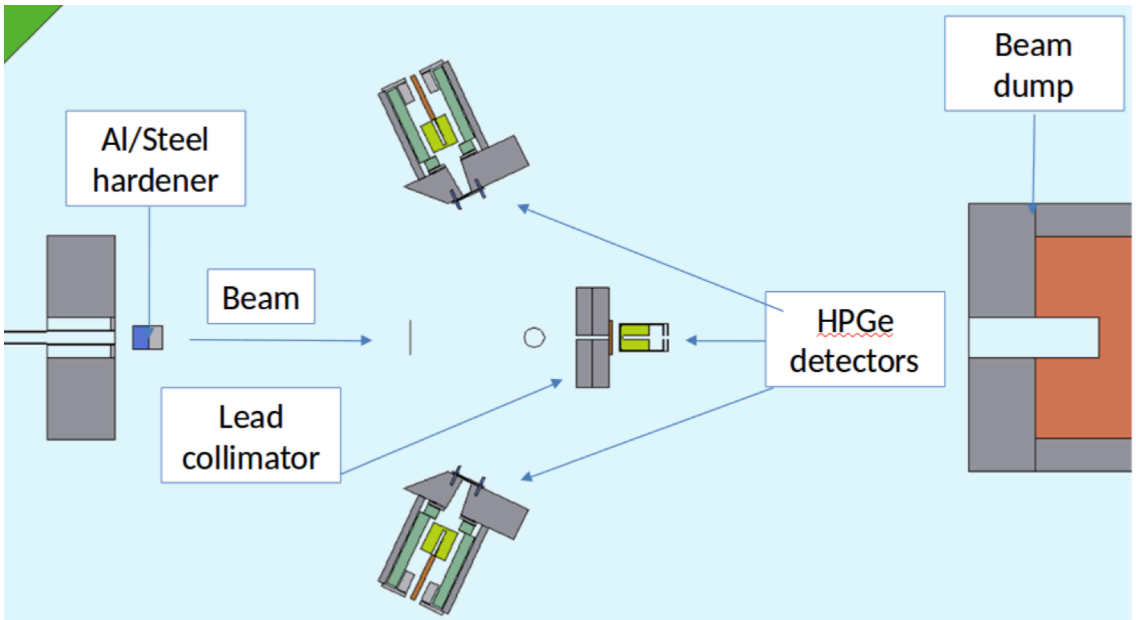
Rate Capabilities

- Up to 150kHz rates expected for Mu2e STM detectors
- gELBE Bremsstrahlung facility at HZDR used to study performance of a HPGe detector in high beam pulse occupance (up to 80kHz)
- gELBE pulse separation 2.4µs close to Mu2e 1.7µs

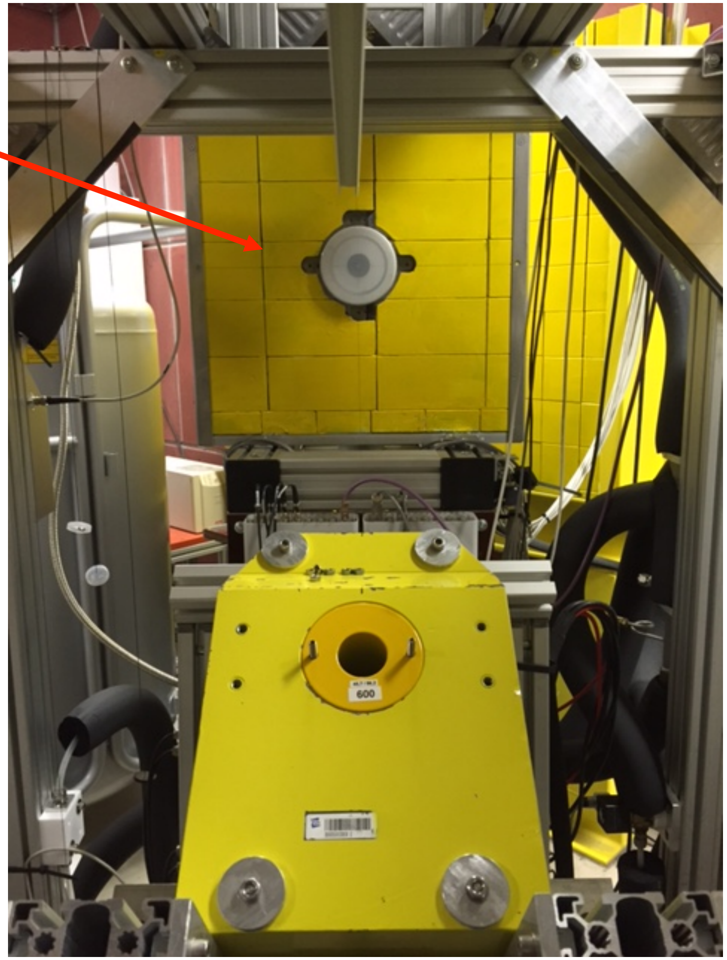


gELBE Beam

- 6-16 MeV e^- beam onto 2cm diameter niobium target behind cave wall (in accelerator hall)
- Bremsstrahlung produced
- Use an aluminum beam hardener to suppress the low energy Bremsstrahlung photons
- End-point energy between 9 and 18MeV

gELBE Beam

- Bremsstrahlung beam collimated by 2.6m long high-purity aluminum tube
- 10^8/MeV Brem photons per second at the secondary target position
- Beam rate constant over time, controlled by ELBE
- ^{137}Cs and ^{60}Co sources placed close to detector



Rate Studies

Timestamp	MWD Energy
145711016	1545
145712008	3659
145714458	134
145714961	1953
145715946	2512
145717414	3185
145720871	155
145721599	456
145724797	3681
145726275	2856
145729485	4222
145730717	3187
145731197	4466

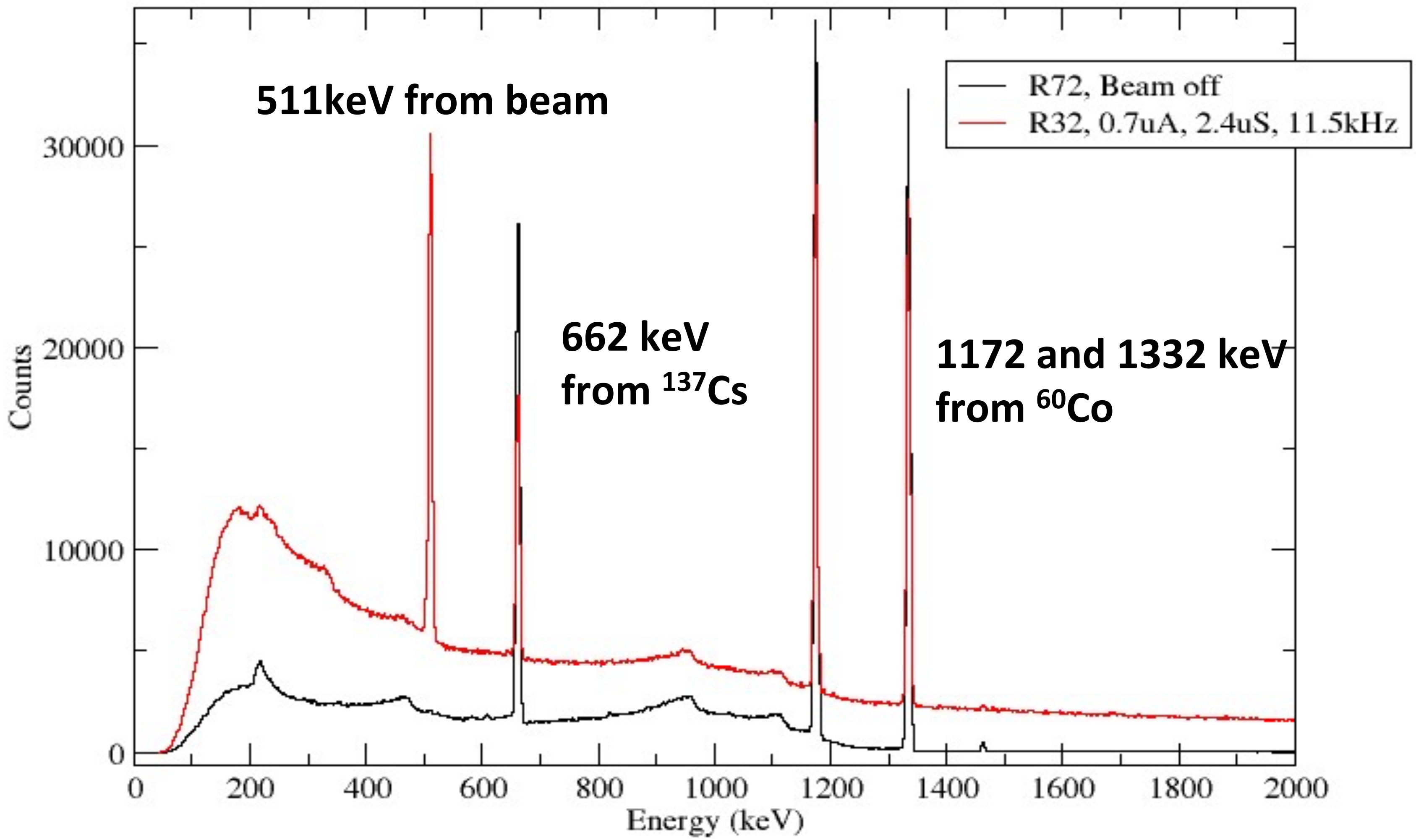
Data Acquired

- HPGe and beam signal into CAEN V1724 digitizer (100 MHz 14 bit ADC)
- NaI and beam signal into CAEN V1724 digitizer
- Digitised traces and timestamps
- Energy spectra

Analysis

- Analysis of spectroscopic performance from energy spectra
- Calculation of energies from digitised traces using various algorithms
- Risetime analysis of traces
- Timestamp correlations with beam pulses

Rate Studies



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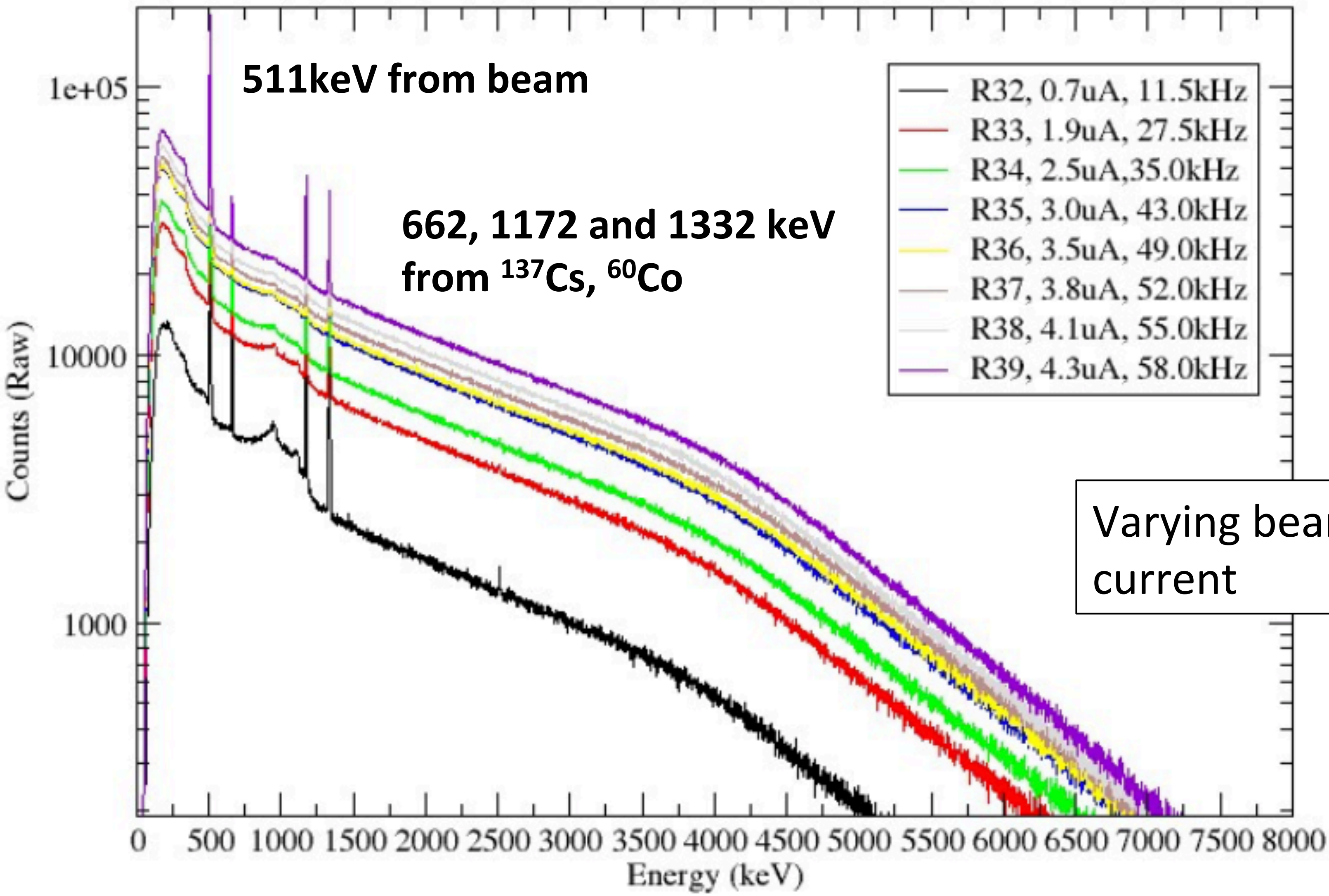
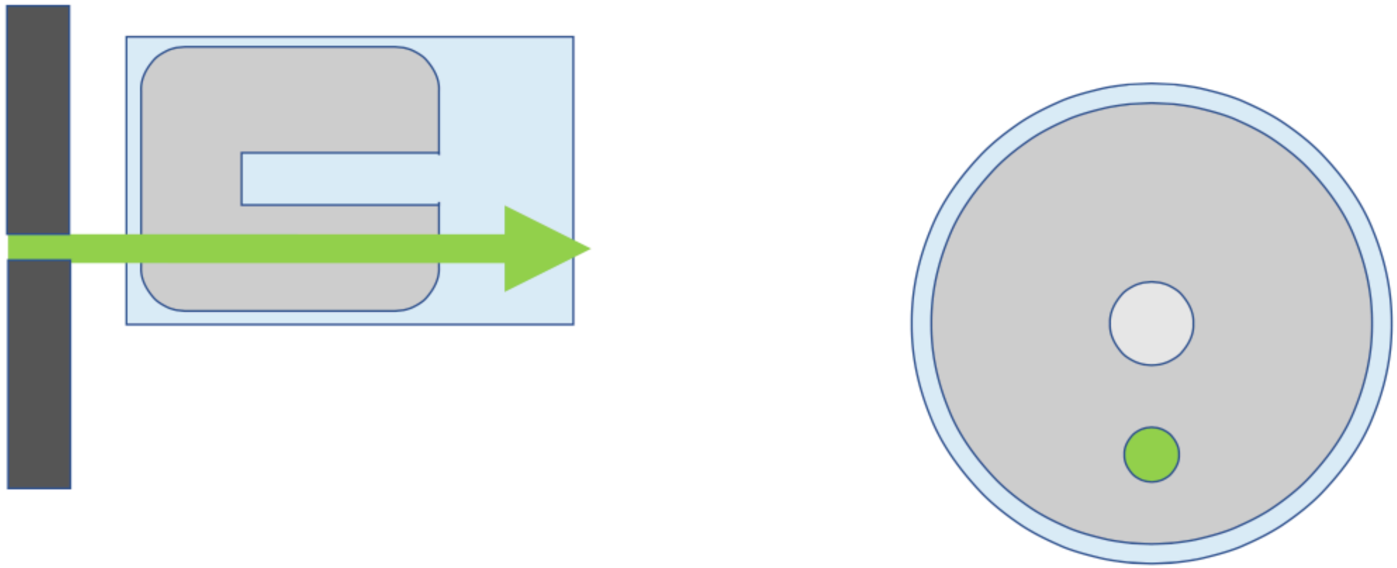


Varying beam current

Rate Studies

Position A



Rate Studies

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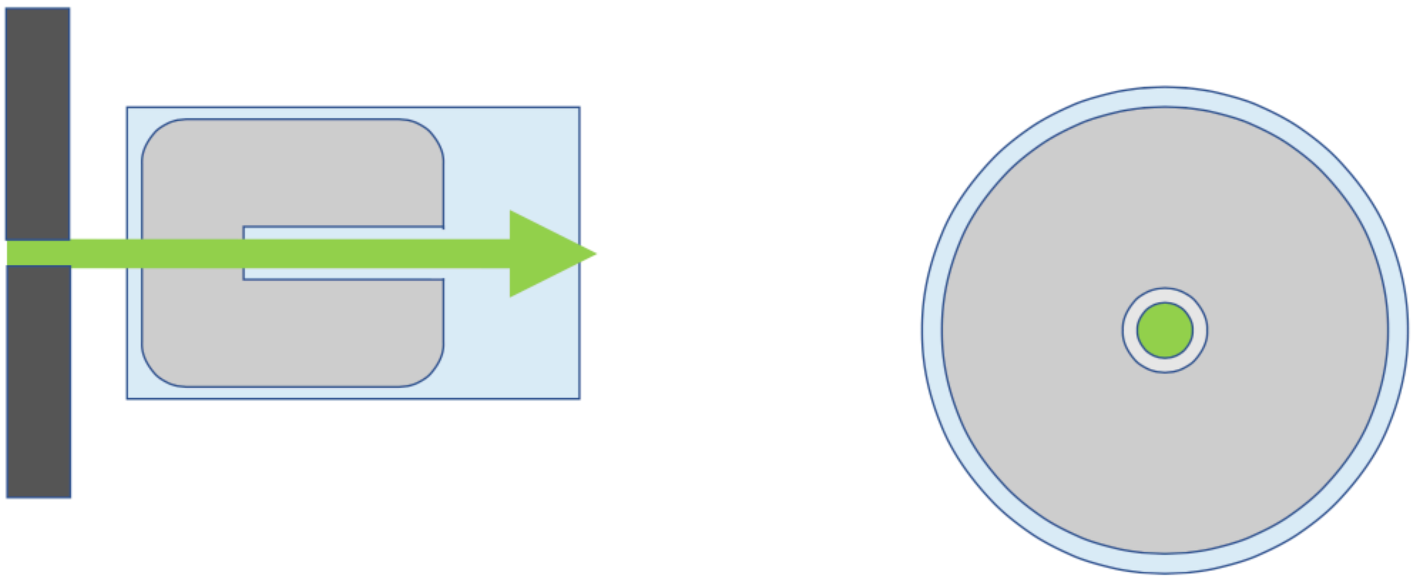
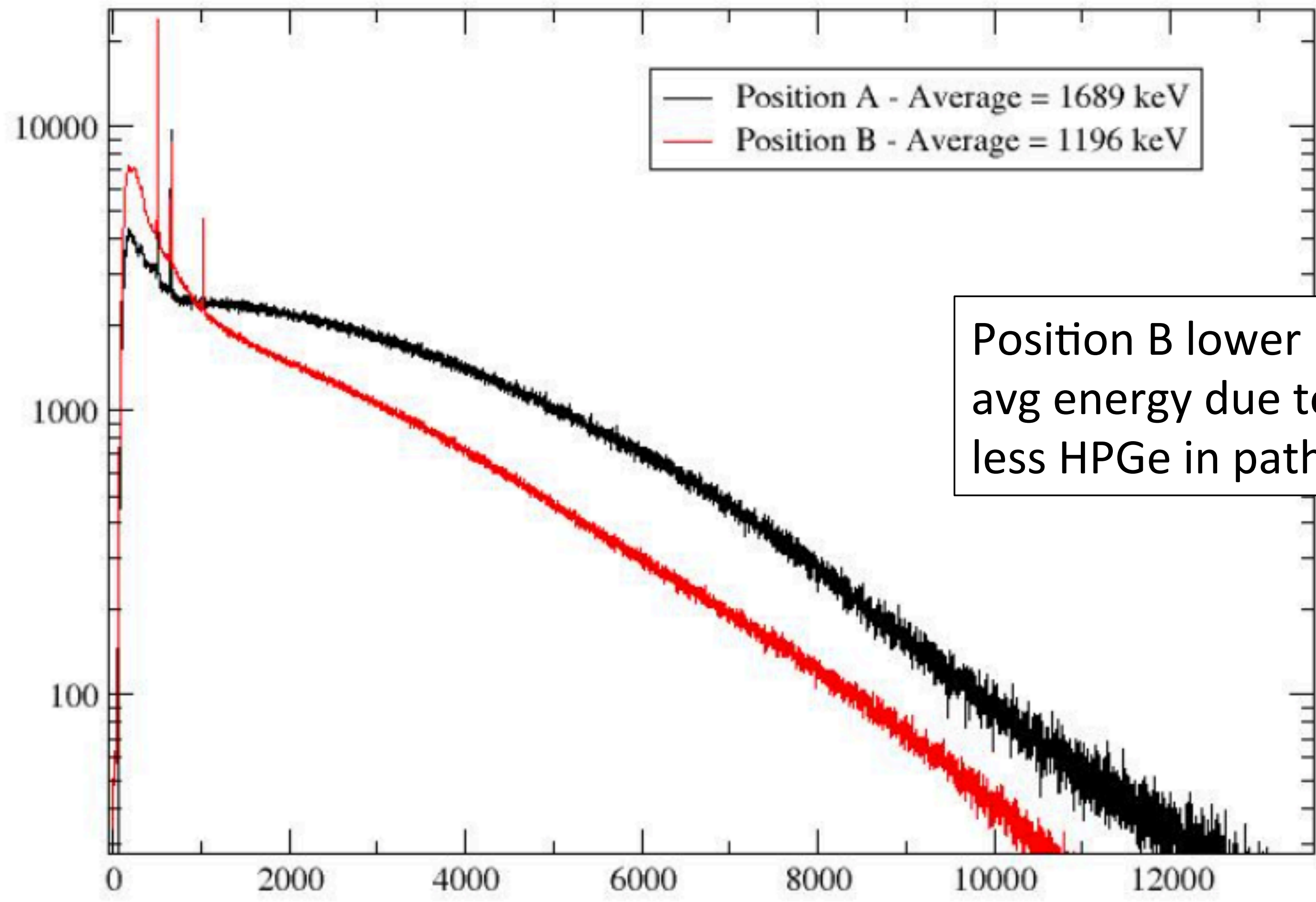
Position B

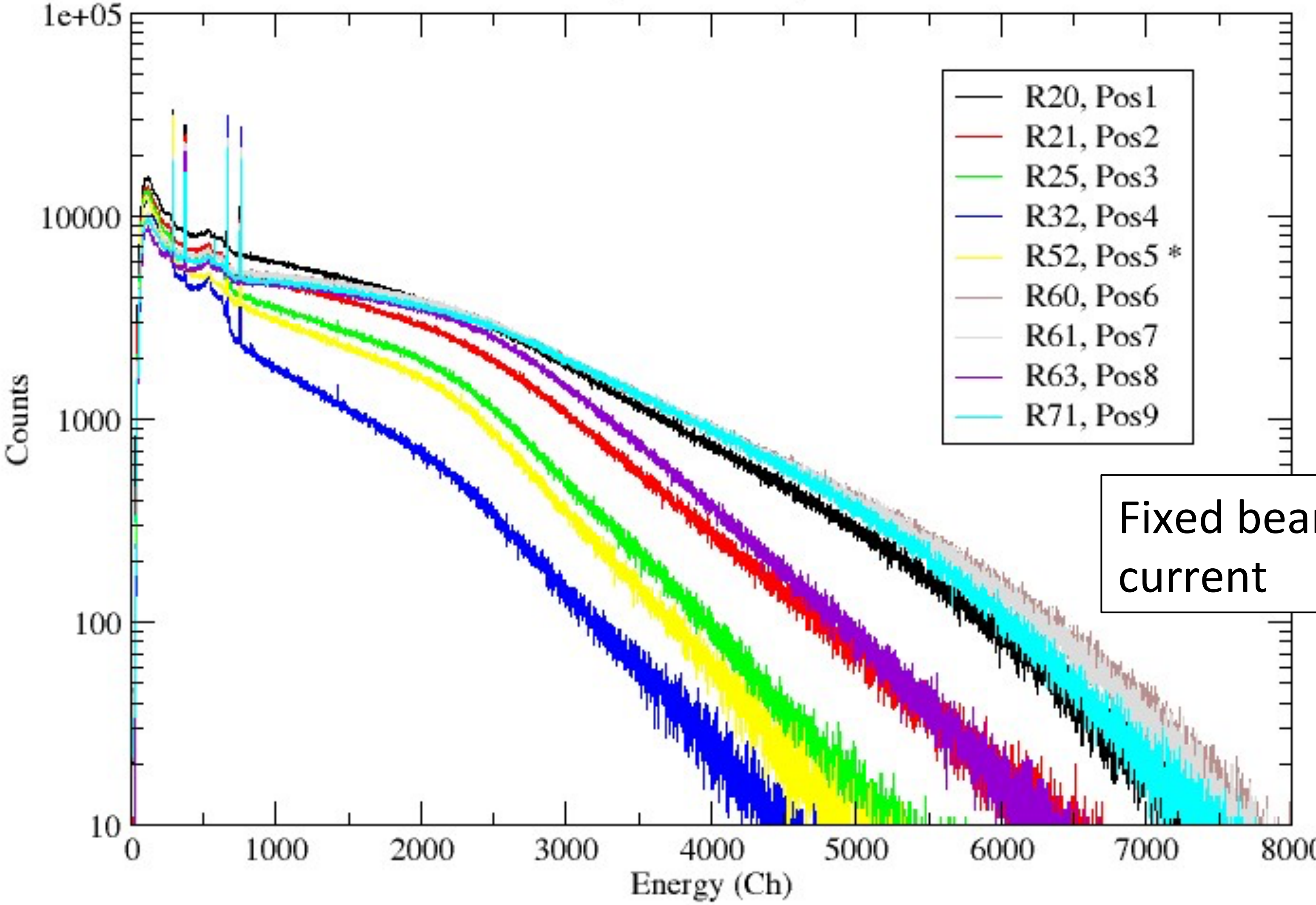


Rate Studies



Position B lower avg energy due to less HPGe in path

Rate Studies

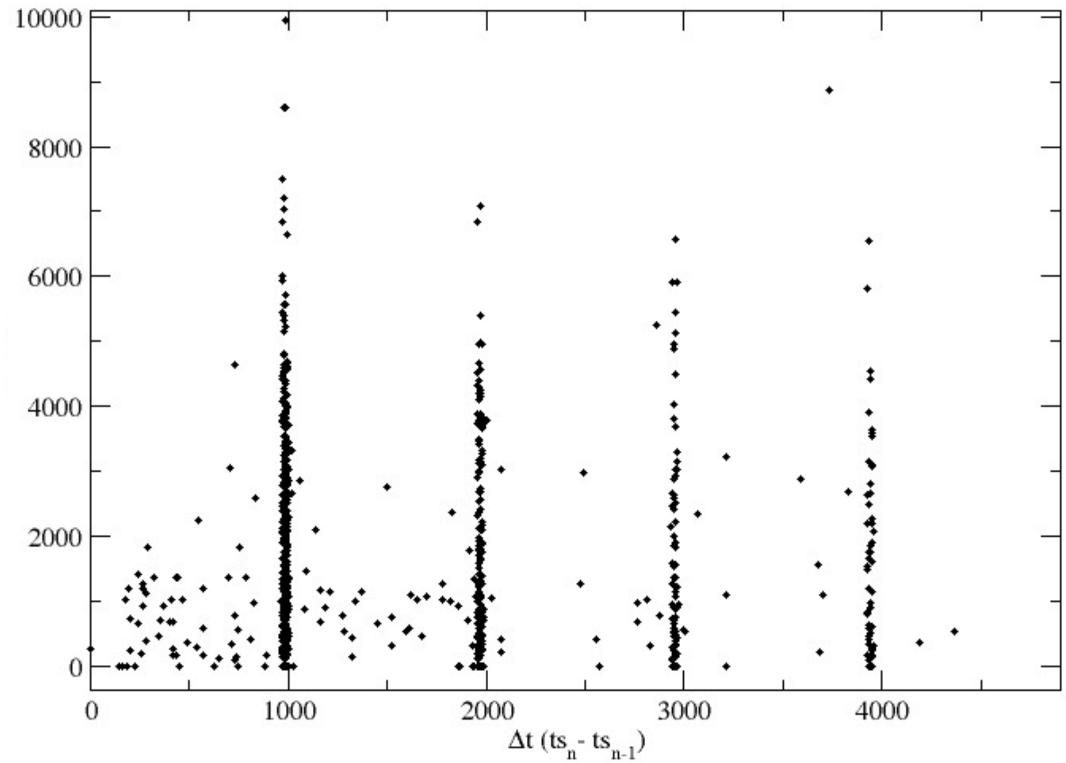


Fixed beam current

Rate Studies

- Calculated the difference in time stamps between subsequent events, $ts_n - ts_{n-1} = \triangle ts$

Timestamp	MWD Energy	$\triangle$ts
145711016	1545	0
145712008	3659	992
145714458	134	2450
145714961	1953	503
145715946	2512	985
145717414	3185	1468
145720871	155	3457
145721599	456	728
145724797	3681	3198
145726275	2856	1478
145729485	4222	3210
145730717	3187	1232
145731197	4466	480



- First 1k events in file
- 10μs beam pulsing data
- $\triangle$ts shows beam freq
- Events between beam are background and source events

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Rate Studies

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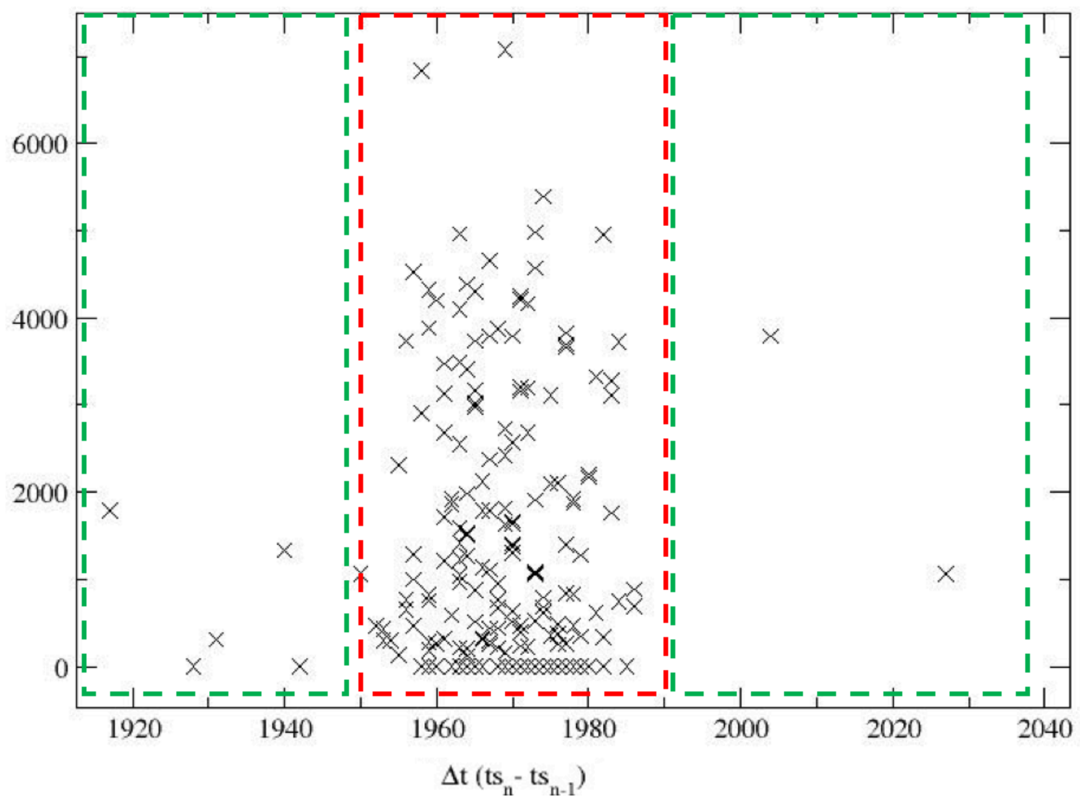

- 9.85μs frequency
- Beam pulse ~ +/- 20 samples wide (~ 400ns)
- Background/source

Rate Studies

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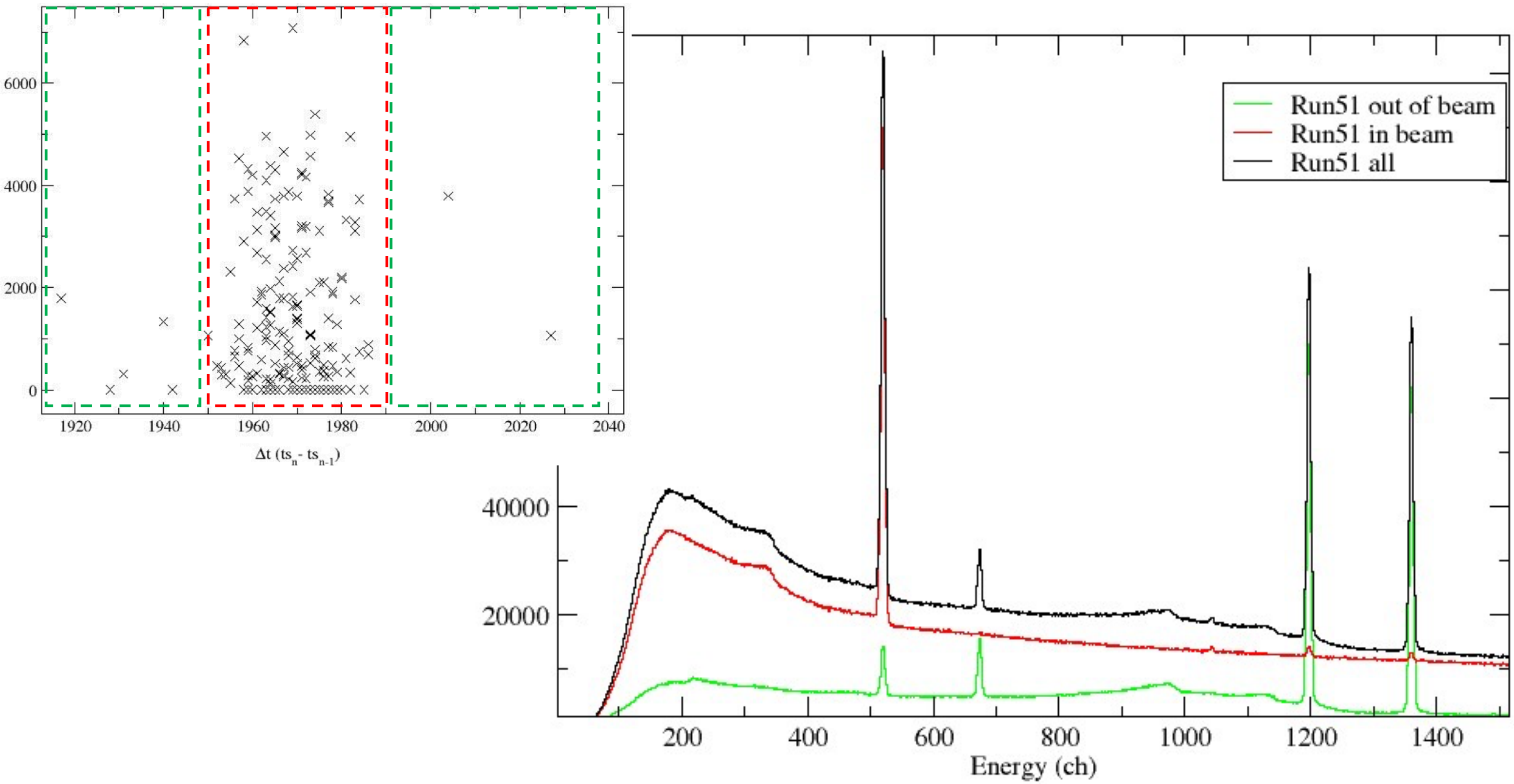
- Energy spectra gated +/- 200ns around beam pulse



Selected detector

- 70% efficiency n-type detector
- X-COOLER3 with umbilical cord
- Internal heater for annealing
- Delivered August 2019

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Summary

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- Mu2e is a search for the coherent conversion of a muon to an electron in the field of an aluminium nucleus
- Observation would be evidence of physics beyond the standard model
- The UK team of Uni of Liverpool, Uni of Manchester and UCL are building the STM: HPGe detector and collimator system with DAQ
- The detectors have been delivered to Liverpool and will be commissioned at Fermilab early 2020.

Collaboration

Argonne National Laboratory
Boston University
Brookhaven National Laboratory
California Institute of Technology
City University of New York
Duke University
Fermi National Accelerator Laboratory
Helmholtz-Zentrum Dresden-Rossendorf, Germany
Institute for High Energy Physics, Protvino, Russia
Institute for Nuclear Research, Moscow, Russia
Istituto Nazionale di Fisica Nucleare, Genova, Italy
Istituto Nazionale di Fisica Nucleare, Lecce, Italy
Istituto Nazionale di Fisica Nucleare Pisa, Pisa, Italy
Joint Institute for Nuclear Research, Dubna
Kansas State University
Laboratori Nazionali di Frascati, Italy
Lawrence Berkeley National Laboratory
Lewis University
Northern Illinois University
Northwestern University
Novosibirsk State University, Russia
Purdue University
Sun Yat-Sen University
University of California, Berkeley
University of California, Davis
University of California, Irvine
University of Houston
University of Liverpool
University College London
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