Experience from operating Germanium detectors in GERDA

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MAX-PLANCK-GESELLSCHAFT

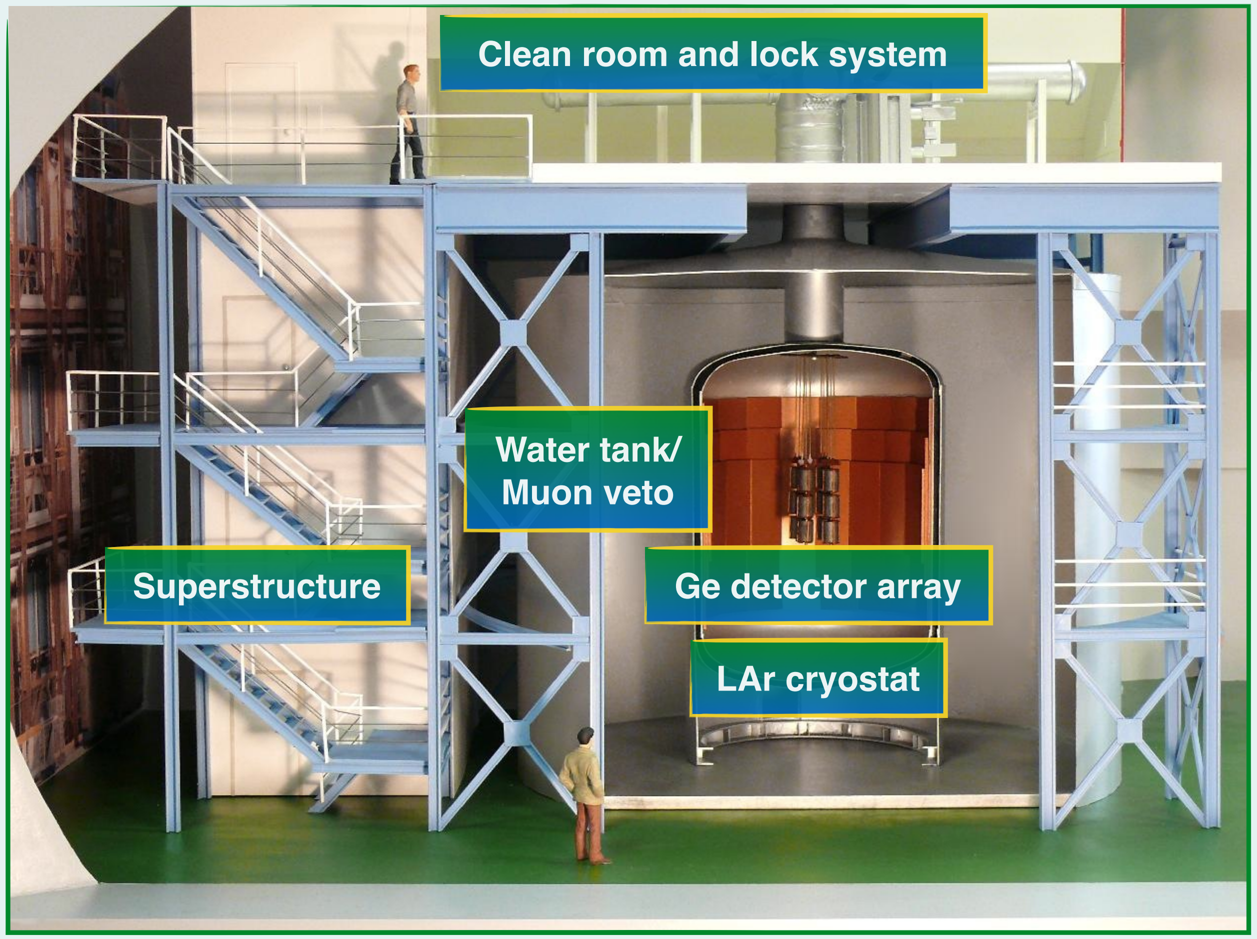
GERDA

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Outline

- the GERDA experiment
- overview of Phase I detectors
- Phase II BEGe detector production
- characterisation of BEGe detectors
    - vacuum tests
    - liquid Argon tests
- summary

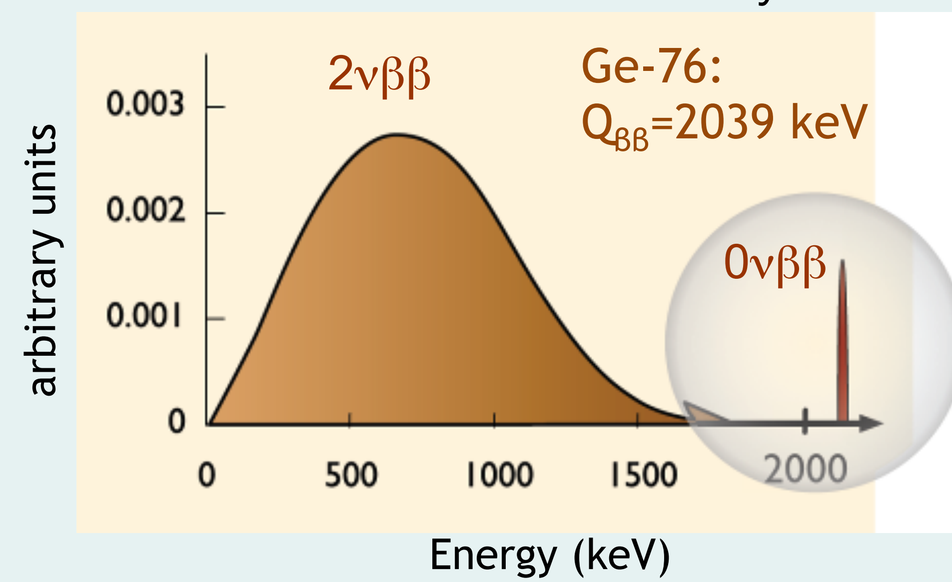
The GERDA experiment



0νββ

$$(A, Z) \rightarrow (A, Z+2) + 2e^{-}$$

- lepton number violation ΔL=2
- physics beyond the Standard Model
- ν have Majorana character
- mass scale and hierarchy

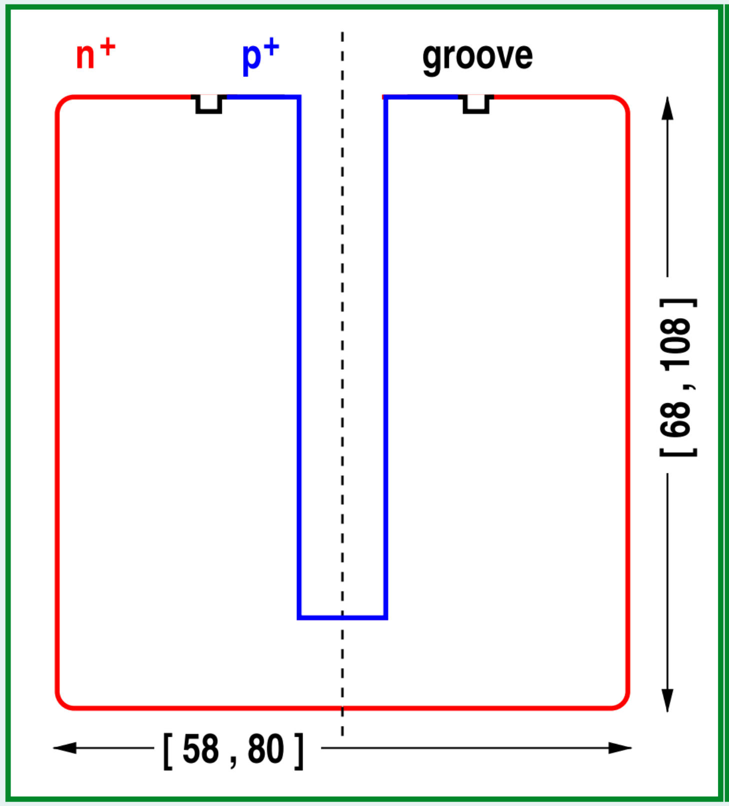


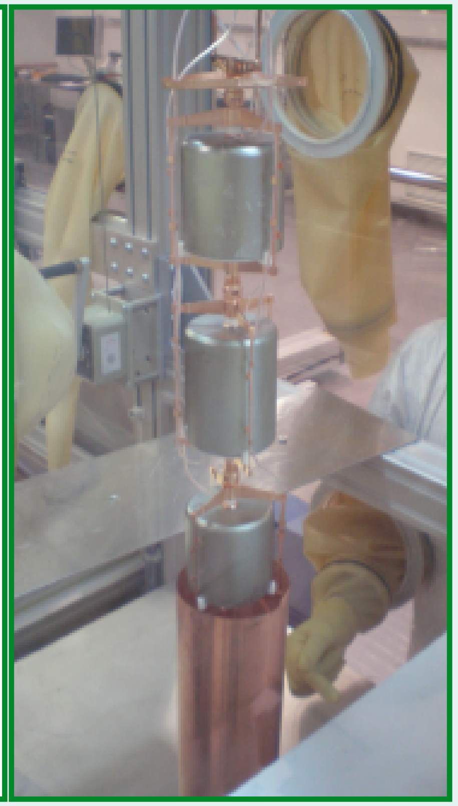
operation of bare Ge detectors in LAr: source=detector, reduced background from cladding material, intrinsically pure, excellent energy resolution, well-established production

GERDA Phase I is complete

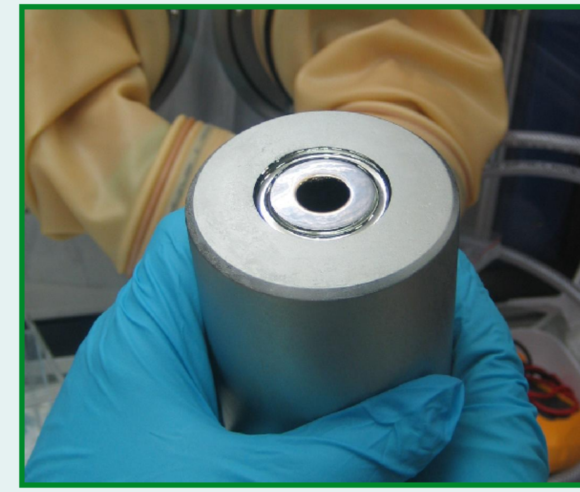
- no 0νββ signal observed
  long standing claim claim strongly disfavoured
- new limit on 0νββ half-life of ^{76}Ge
  $T_{1/2} > 2.1 \times 10^{25}$ yr (90% C.L.)

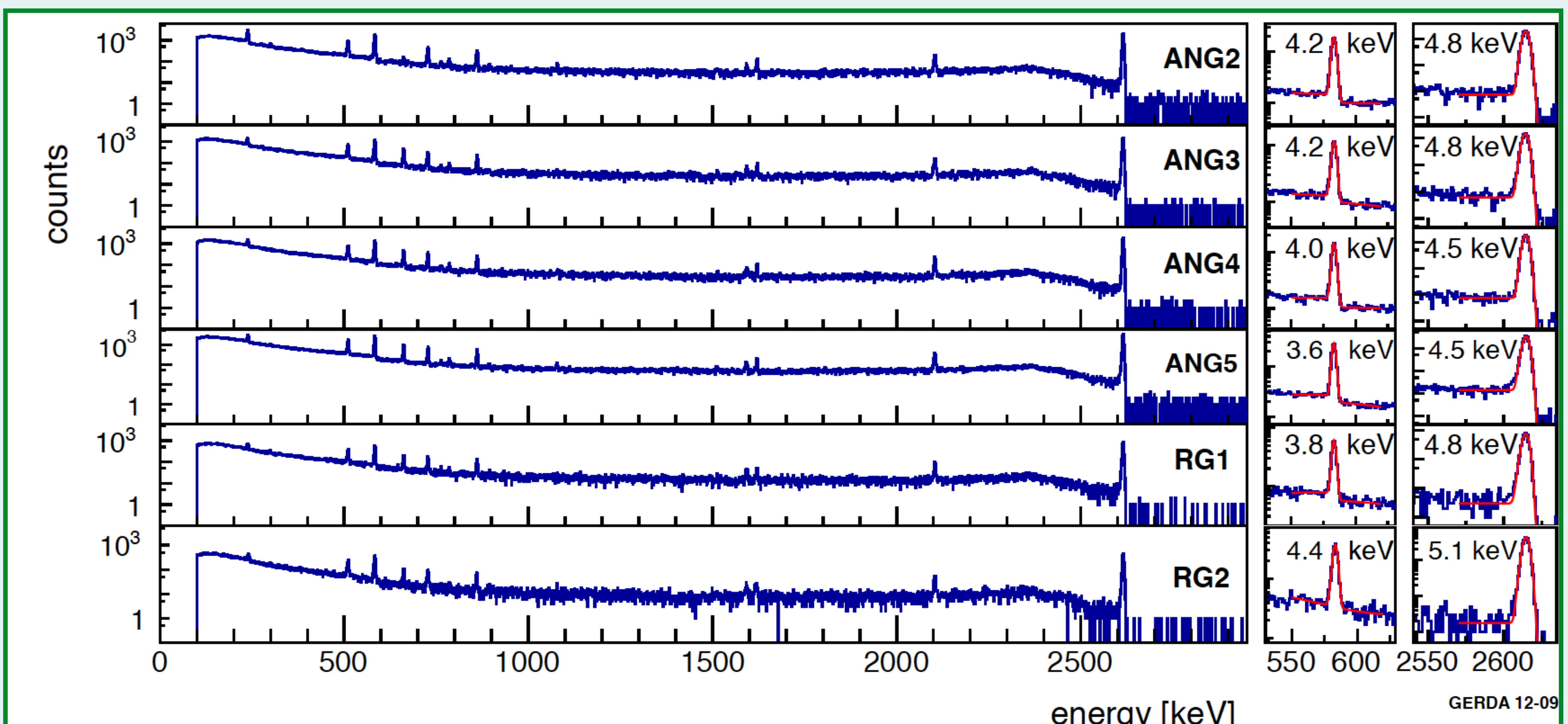
Overview of semi-coaxial detectors





- 8 enriched semi-coaxial p-type HPGe detectors, 14.6kg (refurbished HdM and IGEX diodes)
- ~86% enrichment fraction
- “wrap-around” n+ electrode (lithium dead layer)
- boron implanted p+ contact
- no passivation layer
- 5 BEGe’s (3kg) used in Phase I

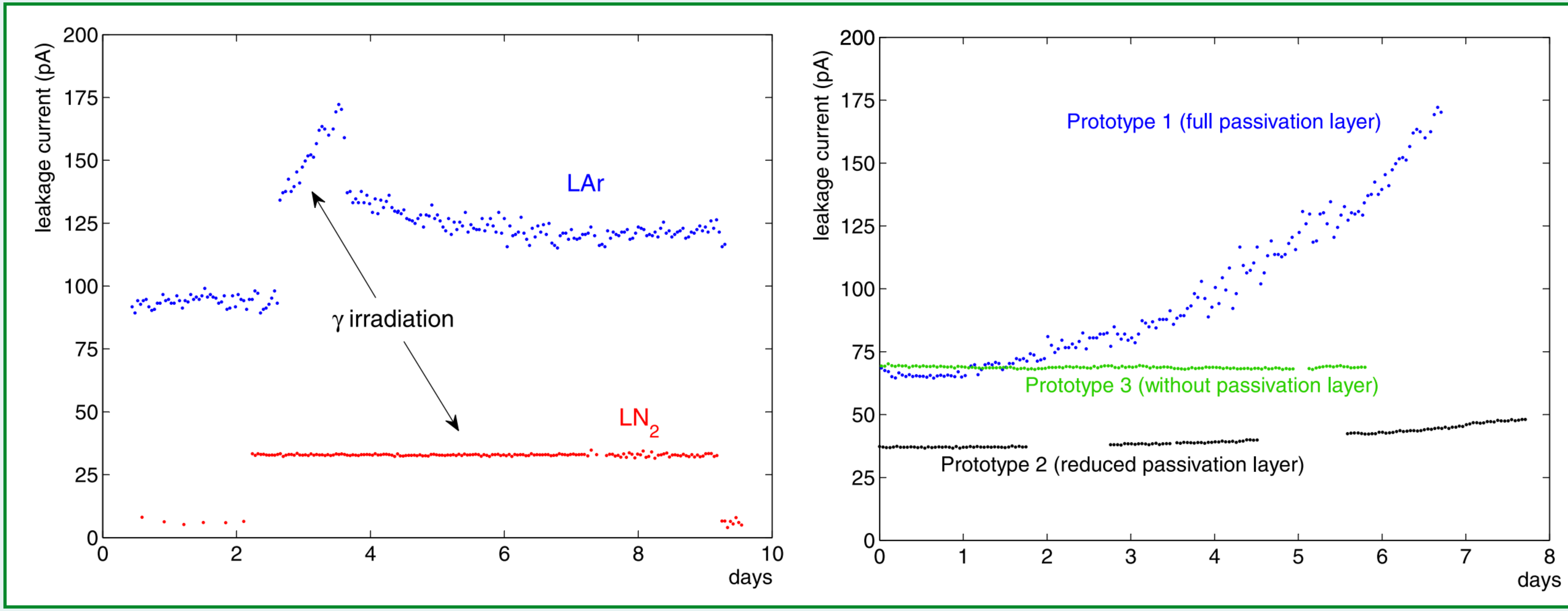




energy resolution at 2.6 MeV (FWHM): 4-5 keV

two detectors developed high leakage current at the beginning of Phase I and have been removed from the analysis

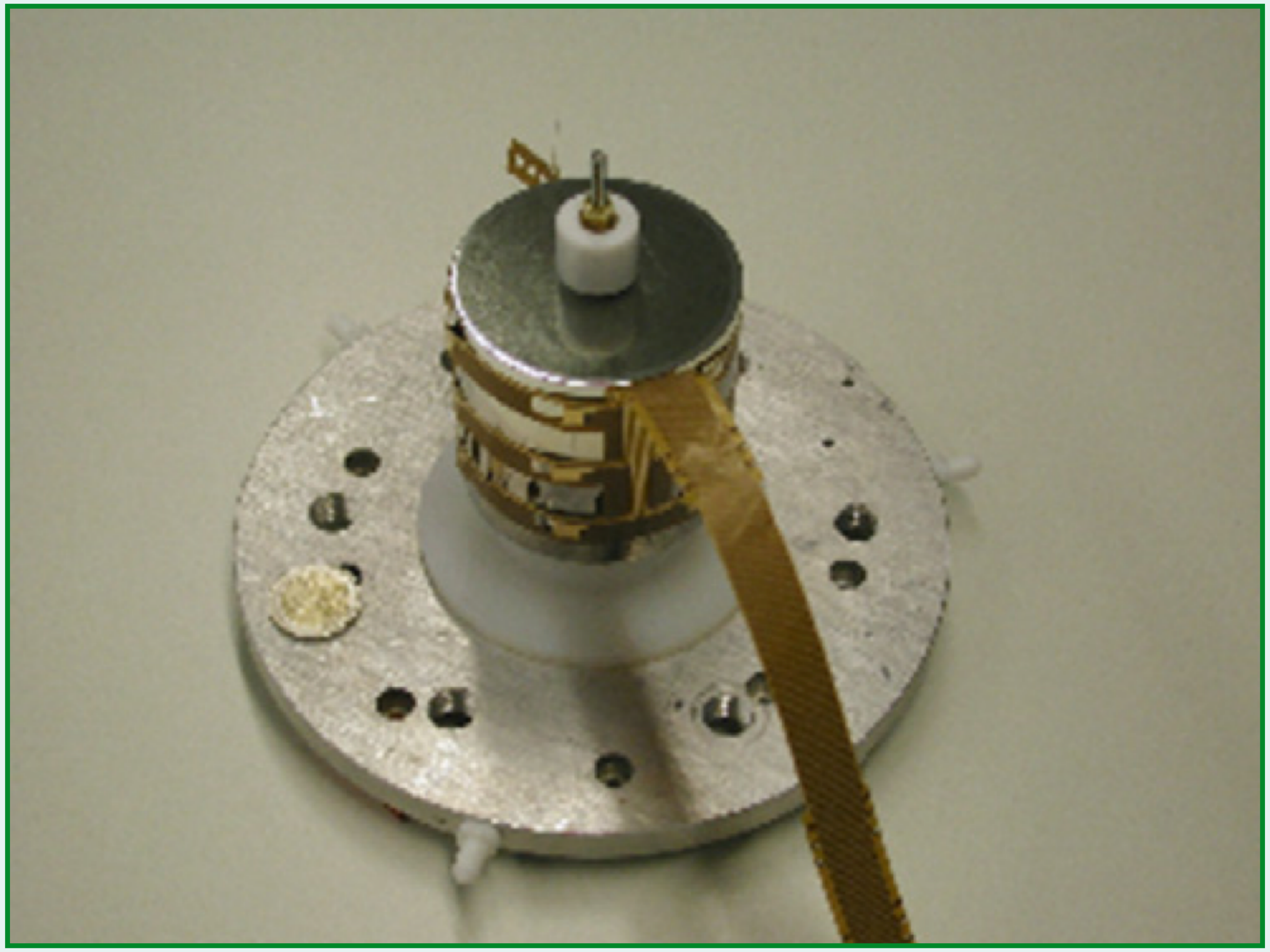
Leakage current (LC)

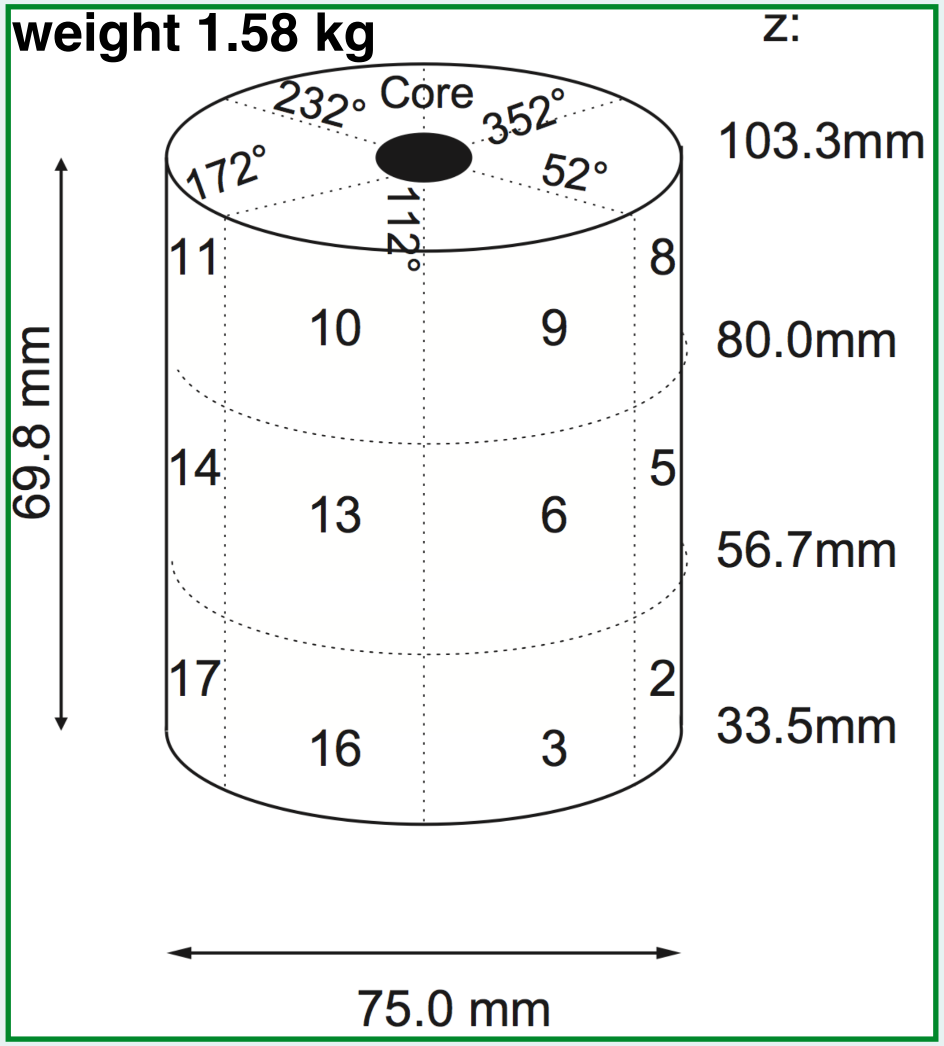


test of bare ^{nat}Ge detectors in LAr and LN$_2$
under γ-irradiation conditions with passivation layer

- continuous increase of LC in LAr (not in LN$_2$)
- stabilisation at higher current after removal of source
- reversible process (detector warmup in methanol baths)
- reducing size of passivation layer suppresses the effect
  (no irradiation induced LC in detector with no passivation layer)
  - collection and trapping of charges on passivation layer
- no evaporation of passivation layer in Phase I detectors

Segmented coaxial detector





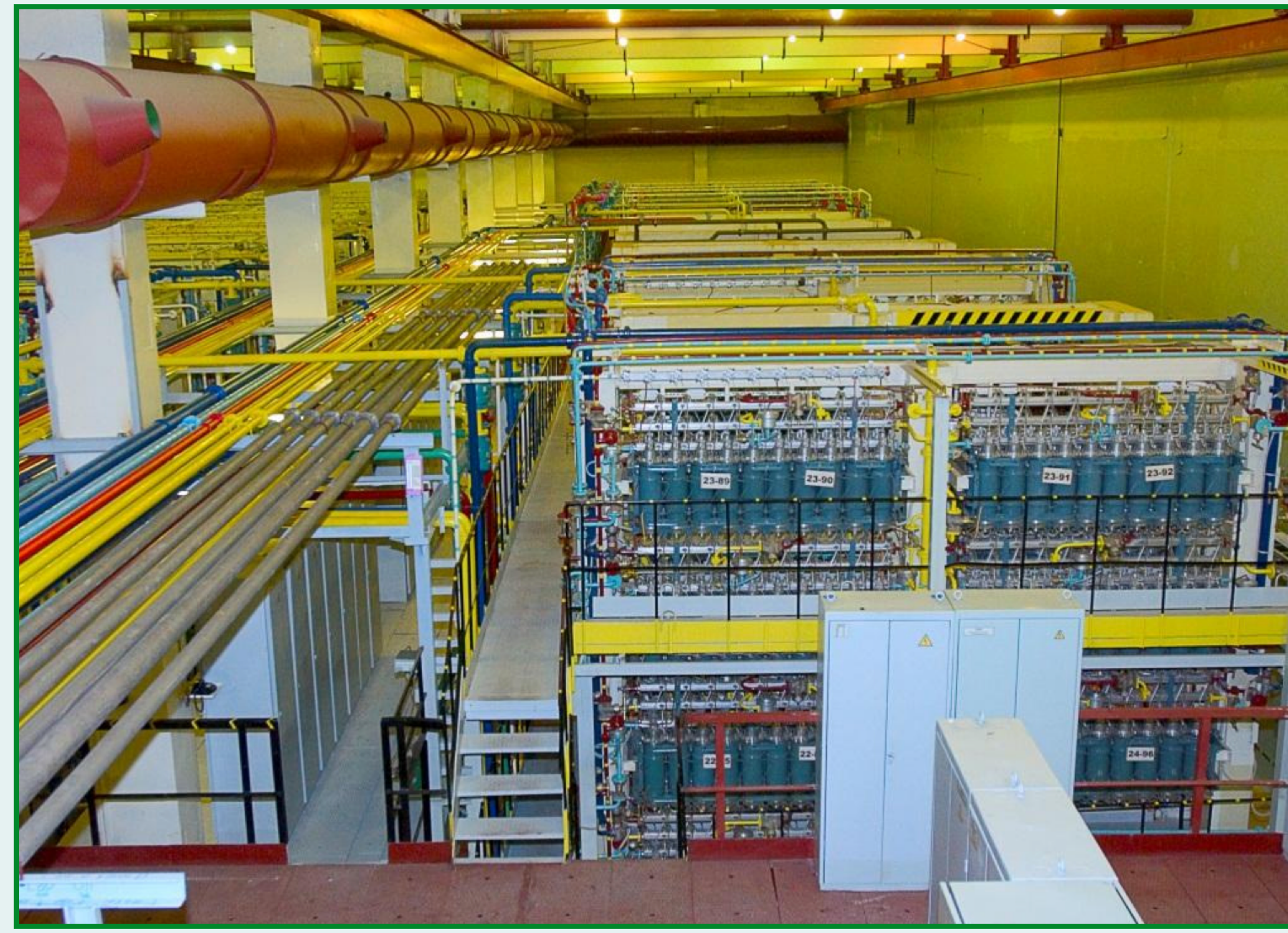
true coaxial 18-fold segmented n-type HPGe prototype detector

- produced by Canberra-France
- tested in Canberra-France and Max-Planck-Institut für Physik, Munich
- worked as according to specifications
- not used in Phase II
  (demanding/expensive technology, many contacts/preamps)

I. Abt et al., Nucl. Instr. and Meth. A 577 (2007) 574

BEGe detector production
Enrichment of ^{76}Ge

- 2005: production at ECP, Zelengorsk, Russia
- 53.3 kg $^{enr}GeO_2$
- 99.99% purity level (4N)
- ~88% ^{76}Ge



Procedure

- natGe fluorination: ^{nat}Ge -> $^{nat}GeF_4$
- centrifugation process: $^{nat}GeF_4$ -> $^{enr}GeF_4$
- hydrolysis procedure with balloons: $^{enr}GeF_4$ -> $^{enr}GeO_2$
- drying and calcination of $^{enr}GeO_2$

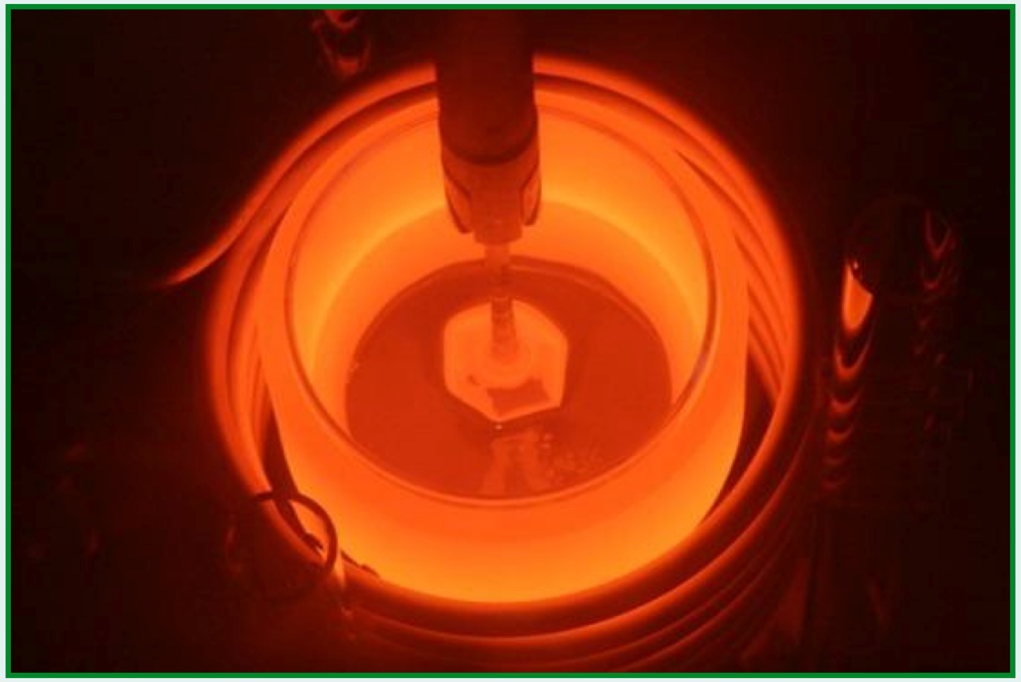
BEGe detector production

Ge reduction, purification and crystal growth

- 2010: reduction and zone refinement,
  PPM Pure Metals GmbH, Langelsheim, Germany
- mass yield of 6N purity electronic grade Ge of 94% produced
- 97% of original 37.5kg available (combined with low resistivity tail)

Procedure

- GeO_2 reduction in H_2 atmosphere to metallic Ge
- cleaning and etching of metal ingots
- zone-refinement (ZR) of ingots
- additional ZR of low resistivity tails of ingots
- etching of metal ingots

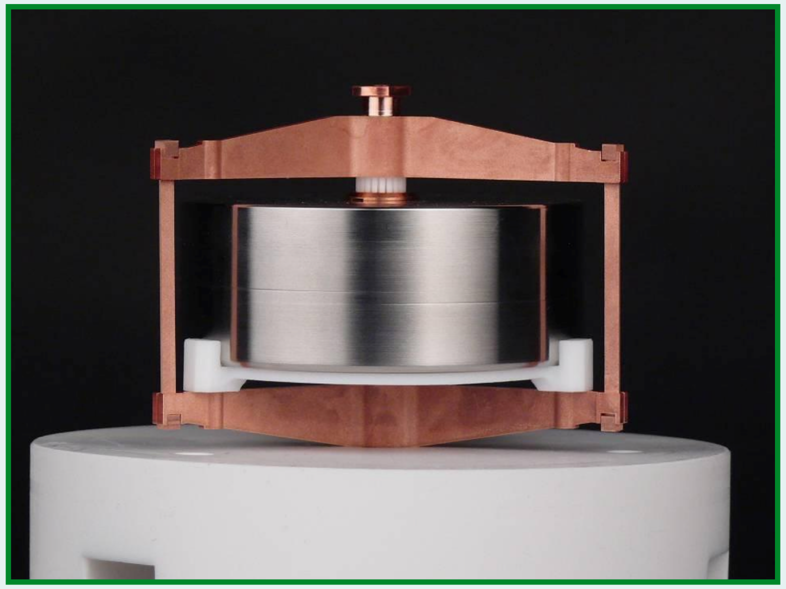


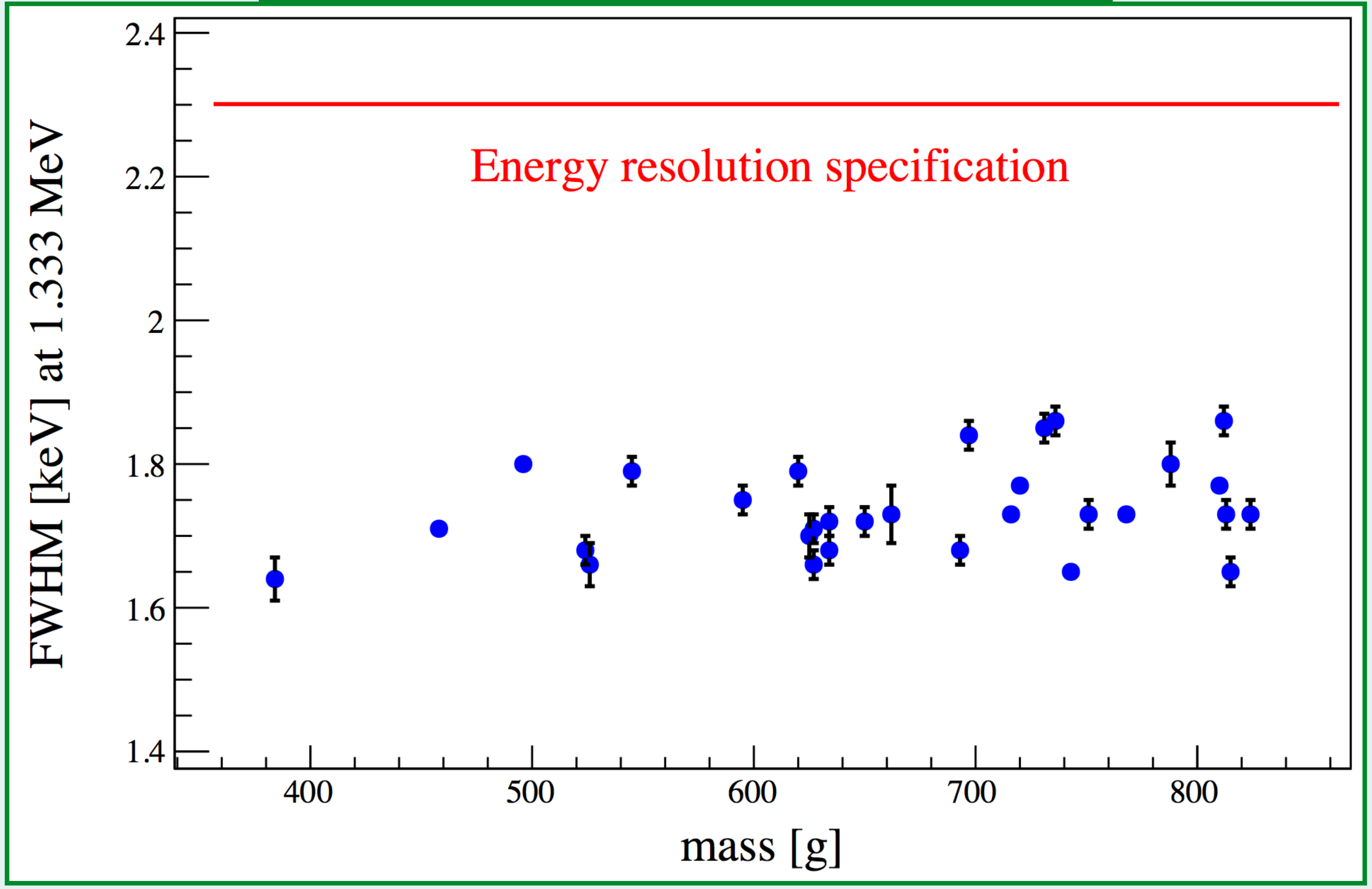
- 2011-12: crystal pulling and cutting, Canberra, Oak Ridge
- 9 crystal ingots, 30 slices (20.8kg)

BEGe detector production
Diode production

- 2012: detector production at Canberra, Olen (Belgium)
- 30 ^{enr}Ge diodes (20kg), 53.3% mass yield
- diodes tested by Canberra in liquid nitrogen bath for specifications on:
  - energy resolution (FWHM) <2.3 keV
  - operational voltage <4 kV
  - leakage current <50 pA

mean energy resolution (FWHM)
1.74±0.07 keV at 1333 keV (^{60}Co)



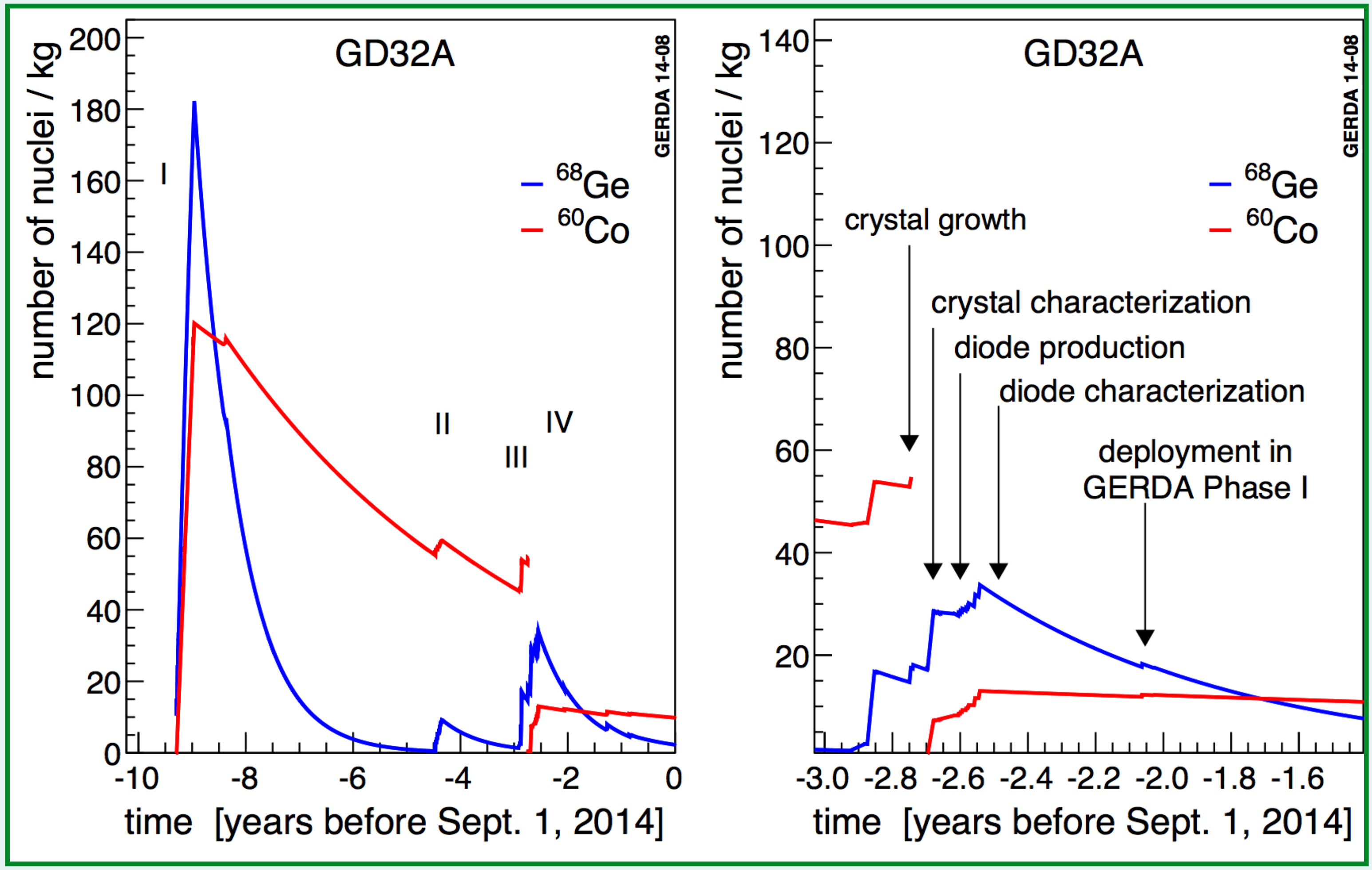


deteriorated charge collection efficiency for one detector:
can not reach full/stable depletion voltage

Cosmic-ray activation of Ge

most important isotopes produced by cosmic activation

- ^{68}Ge, $T_{1/2}$ = 270.8 d
- ^{60}Co, $T_{1/2}$ = 5.2 yr



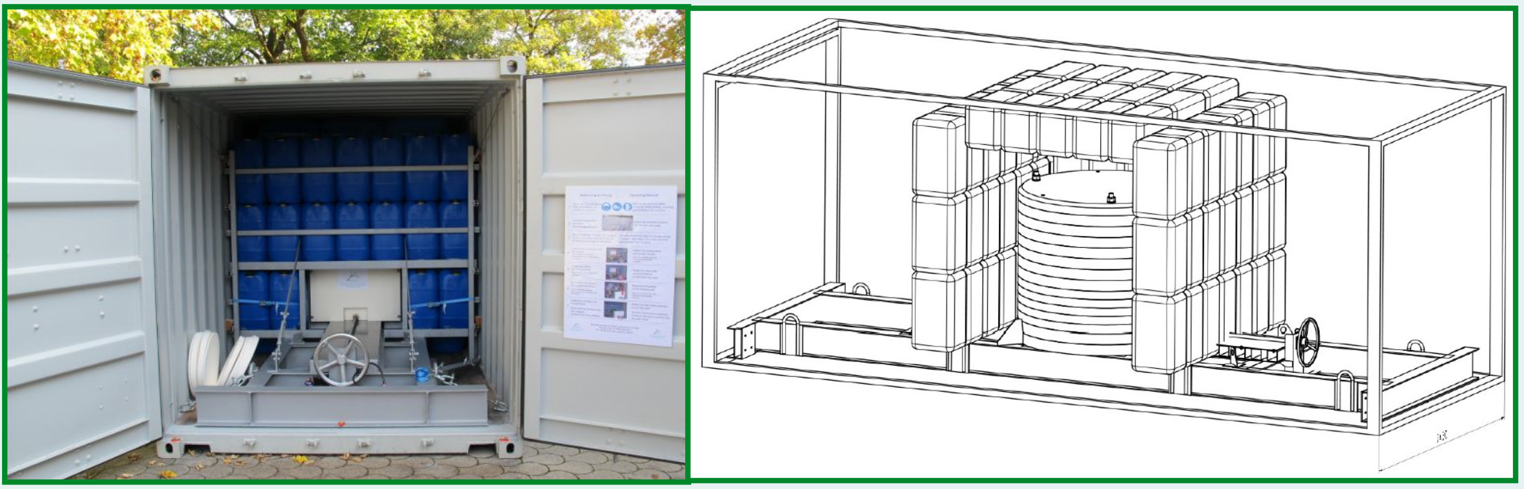
<u>expected B.I. at Q_{bb} (3 yr average)</u>

^{68}Ge

- 3.7×10^{-3} cts/(keV kg yr) before PSD
- 1.8×10^{-4} cts/(keV kg yr) after PSD

^{60}Co

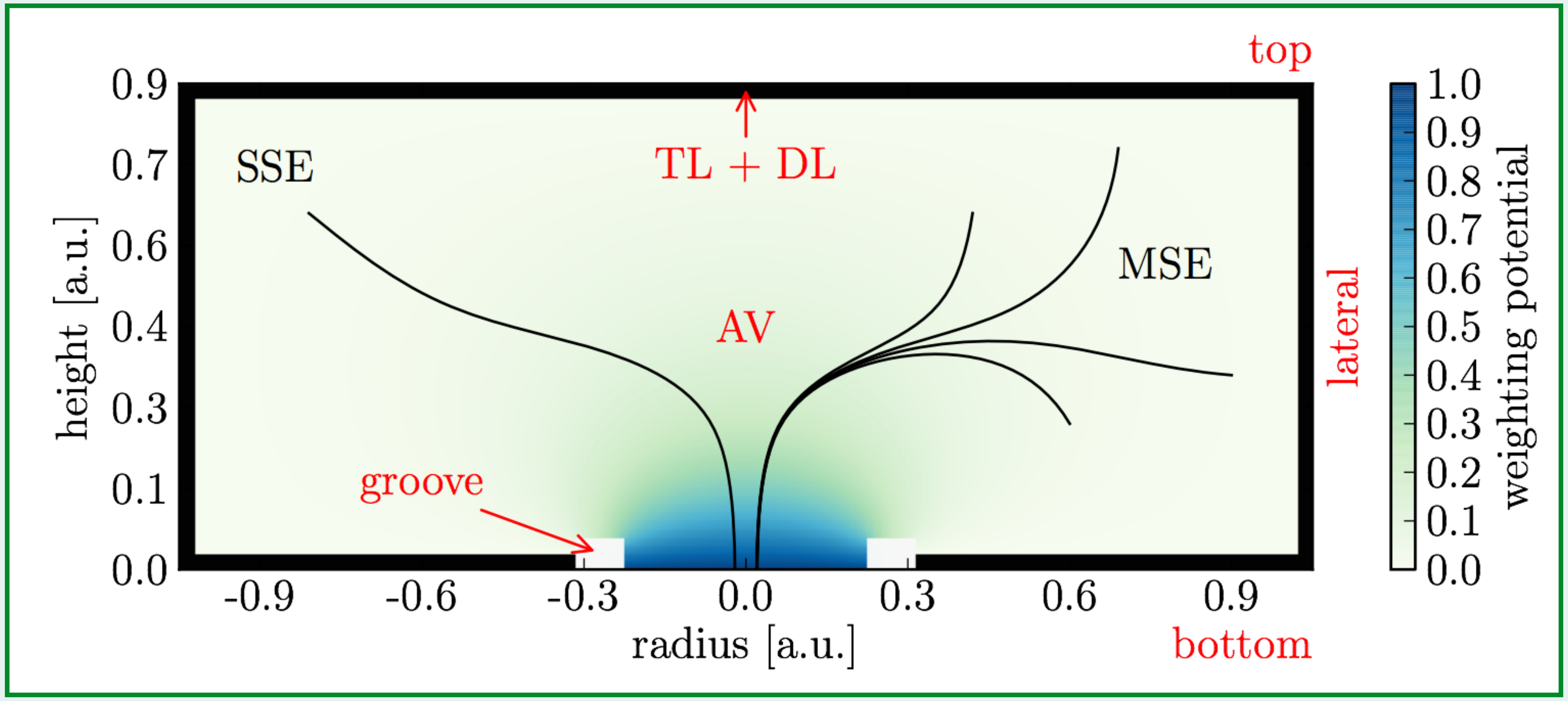
- 8.4×10^{-4} cts/(keV kg yr) before PSD
- 8.4×10^{-6} cts/(keV kg yr) after PSD



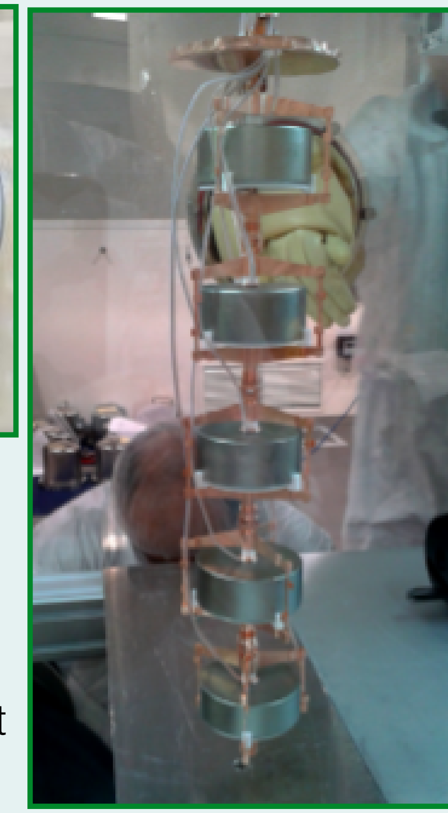
Actions to minimise Ge activation

- optimisation of processing steps
- on-site storage
- shielded transport

Overview of BEGe detectors



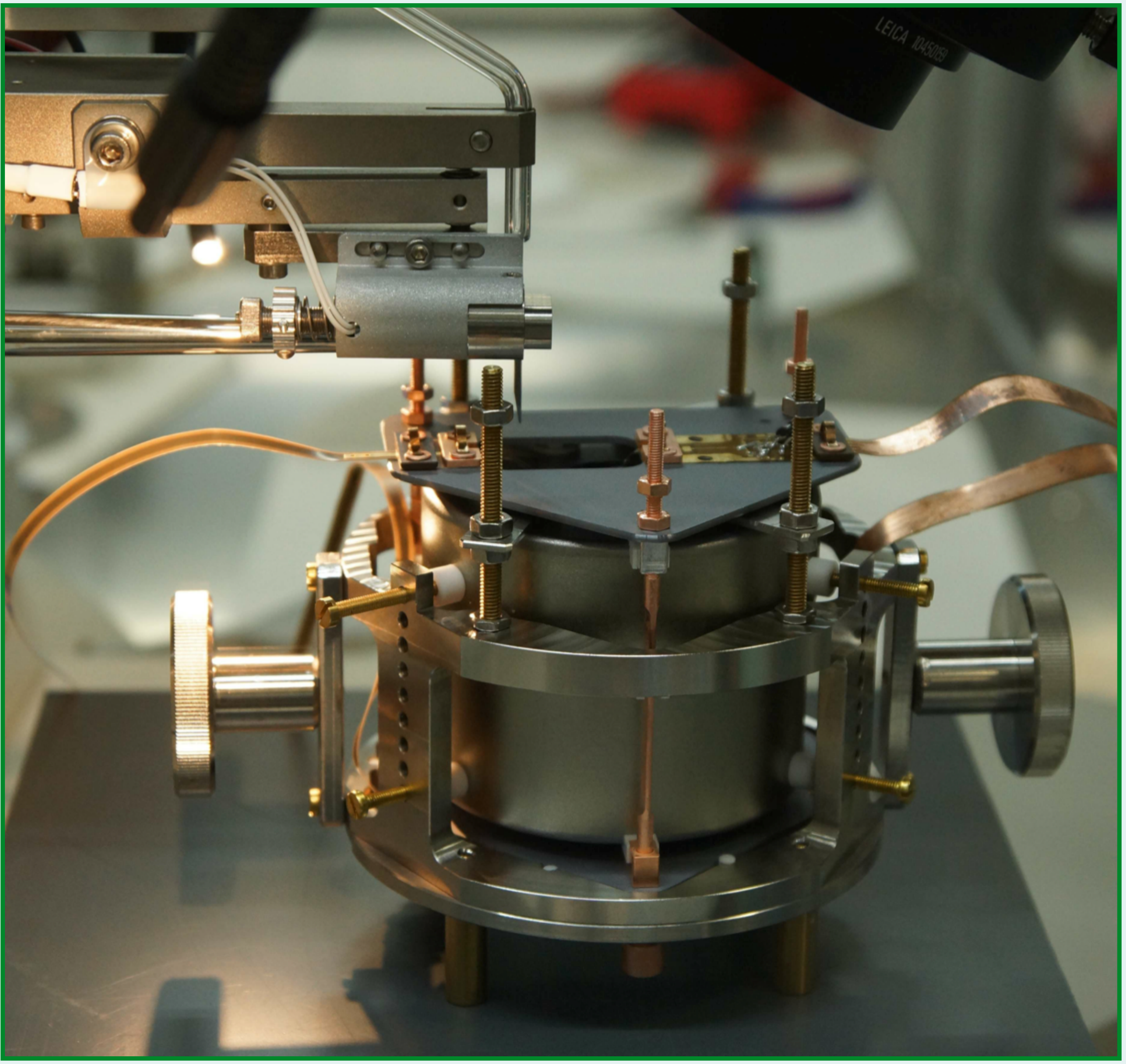
AV: active volume
TL: transition layer
DL: dead layer
SSE: single-site event
MSE: multi-site event



- p-type Ge crystal
- ~88% enrichment fraction
- “wrap-around” n+ electrode (lithium dead layer)
- p+ electrode
- reduced passivation layer thickness
- 5 BEGe’s (3kg) used in Phase I

- smaller size compared to Phase I coaxial detectors
  - average diameter: 73.3 ± 3 mm
  - average height: 29.7 ± 3 mm
- smaller size of read-out electrode (lower capacitance/noise, better E resolution)
- enhanced pulse shape discrimination

Bonding of BEGe detectors



new contacting scheme

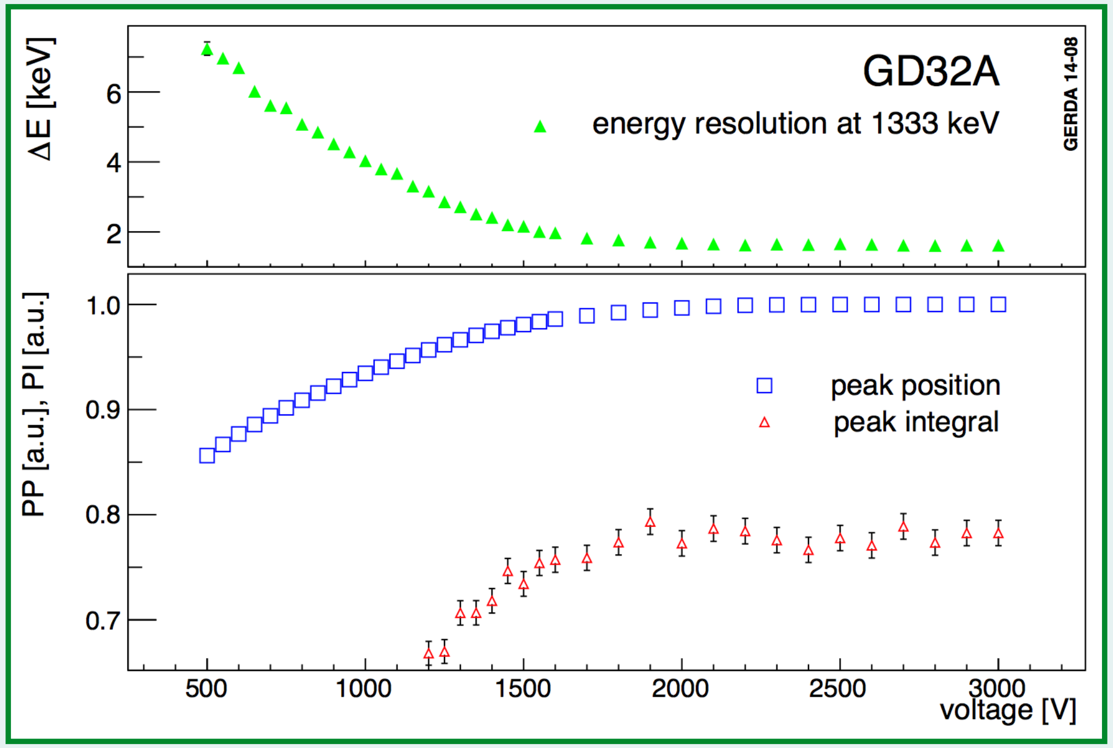
- Phase II BEGe's: ultrasonic wire bonding
  - low mass electrical contact
  - reduced holder mass
- first time in large volume Ge diodes
- 600 nm thin Al film deposited on diodes (Al e-gun evaporation)

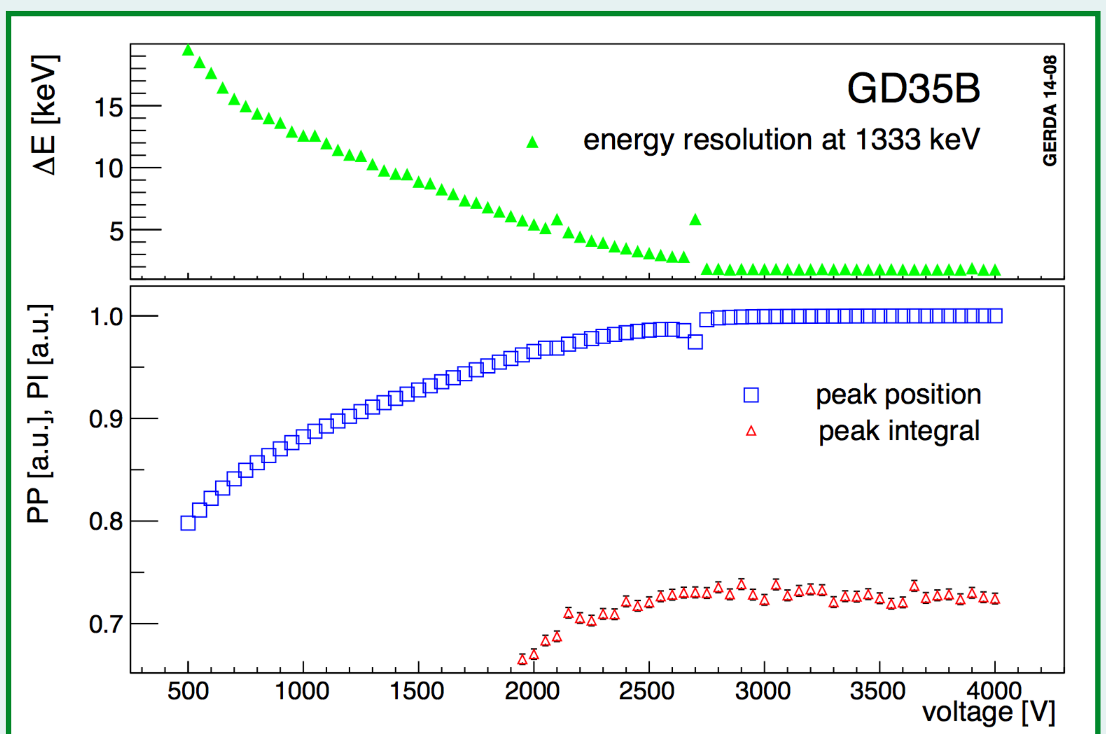
requirements

- wires must be stable in LAr ✓
- survive warming/cooling cycles ✓
- avoid damage to p+ contact ✓

Vacuum cryostat tests

Depletion voltage and energy resolution





- high voltage scans with ^{60}Co source monitoring:
  - peak position
  - peak integral
  - energy resolution

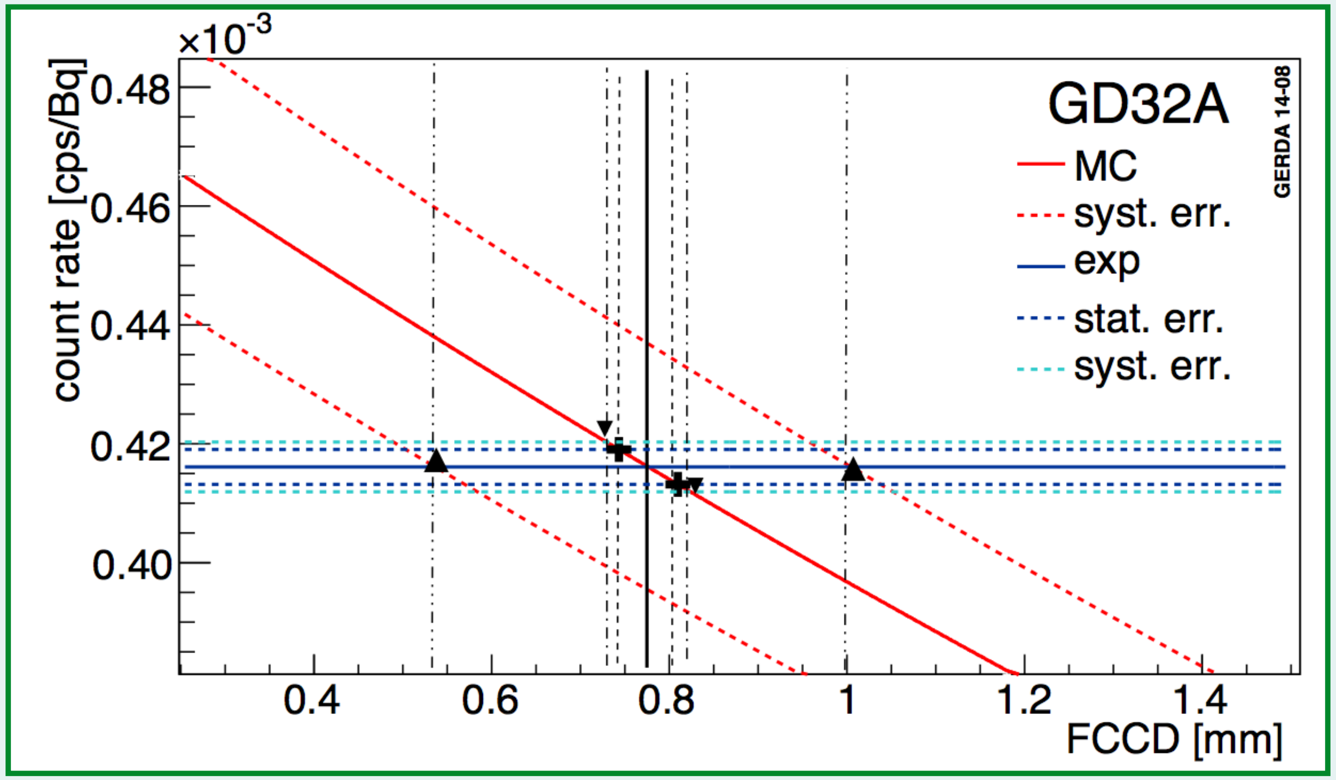
- depletion voltage = recommended V - 500V
- good agreement with manufacturer’s values
- ~30% better E resolution than semi-coaxial
  - 1.73 ± 0.05 keV for ^{60}Co at 1333 keV
  - 2.47 ± 0.05 keV for ^{208}Tl at 2615 keV
- “bubble”/“pinch-off” effect before depletion

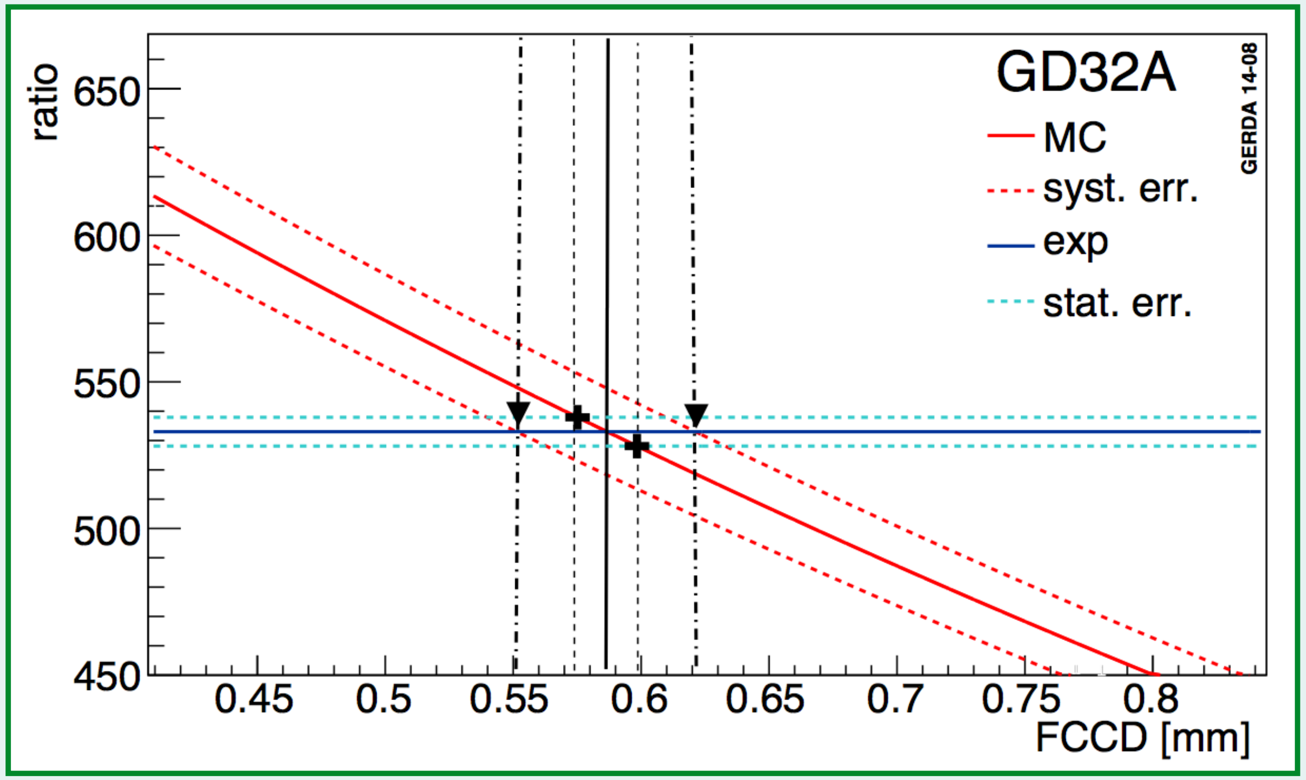
testing at HADES underground lab, Mol, Belgium

Vacuum cryostat tests
Active volume determination

- peak count rate method, ^{60}Co
- dependent on precise activity knowledge

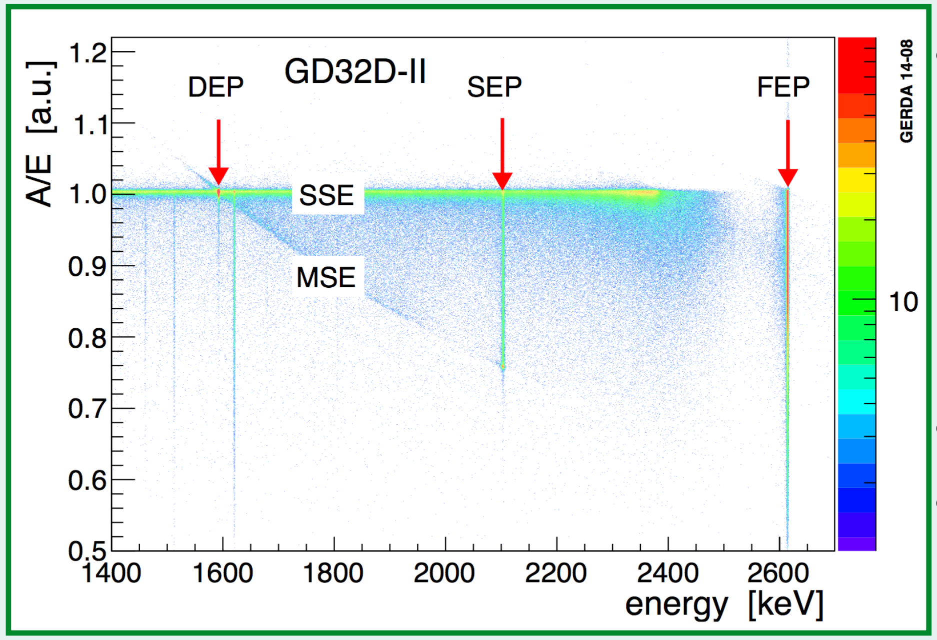
- peak ratio method, ^{241}Am
- activity independent





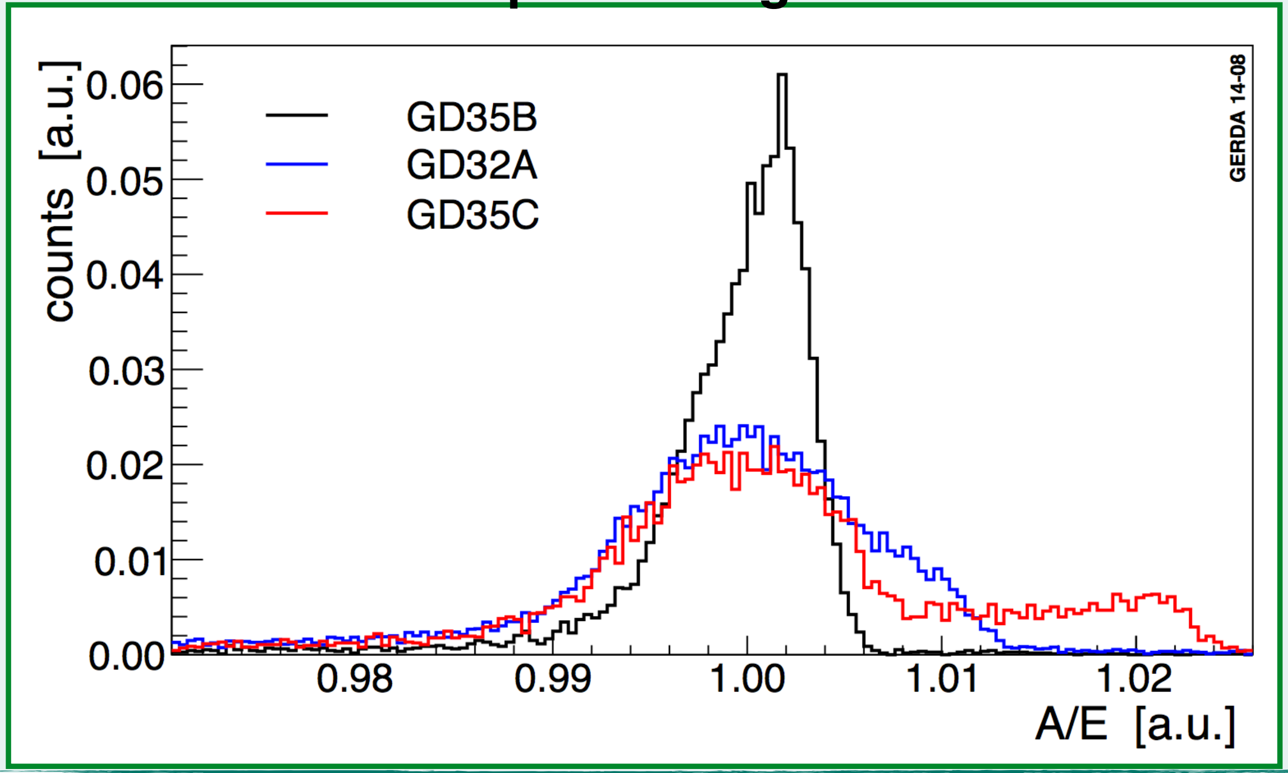
- active volume fractions: (89-94)%
- good agreement with ^{241}Am results from manufacturer
- ^{60}Co results are systematically lower than ^{241}Am by 1.9%

Vacuum cryostat tests
Pulse shape analysis



- ^{228}Th calibration source
  - SSE proxy
    Double Escape Peak at 1593 keV
  - MSE proxy
    Full Energy Peak, Single Escape Peak, Compton continua
- mono-parametric A/E method
- background survival @ROI ~33% (at 90% acceptance @DEP)

A/E distribution for DEP:
Gaussian with Compton background tail

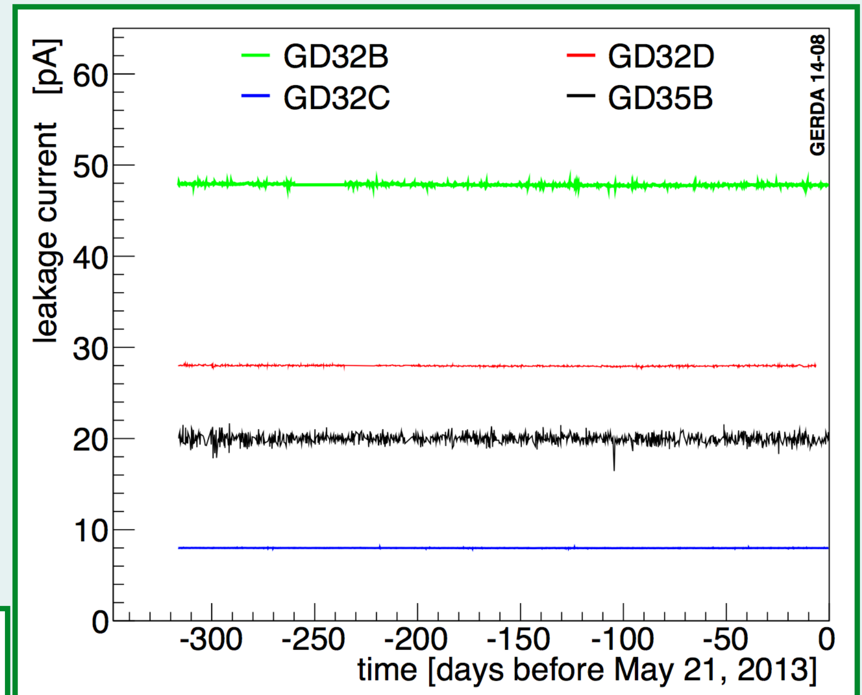


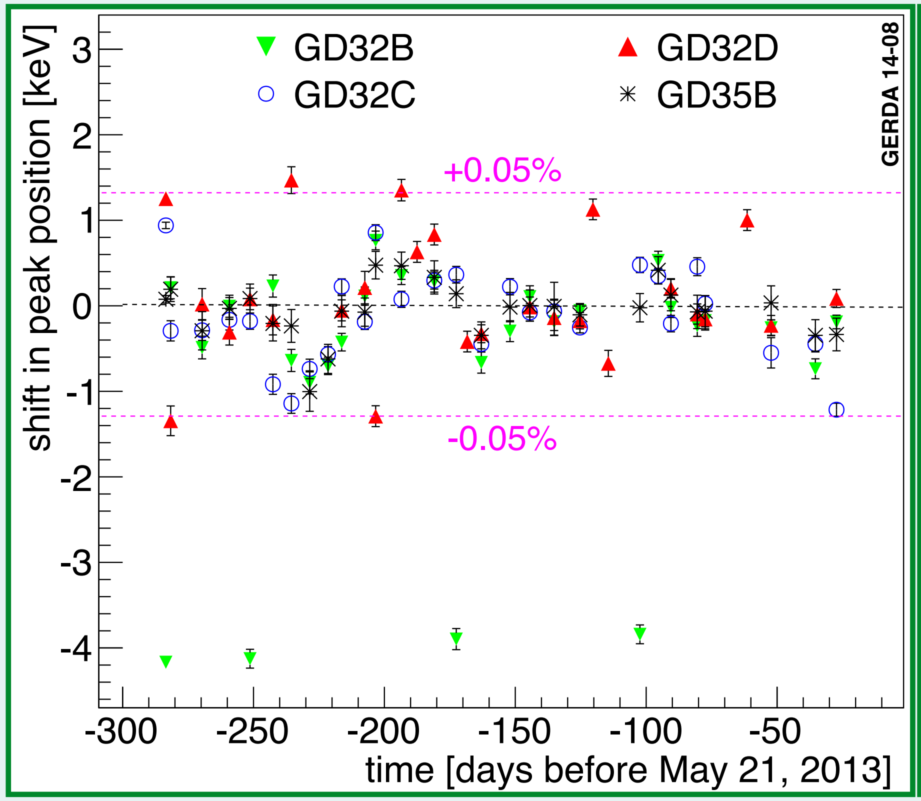
5 BEGe's show anomalous A/E distributions

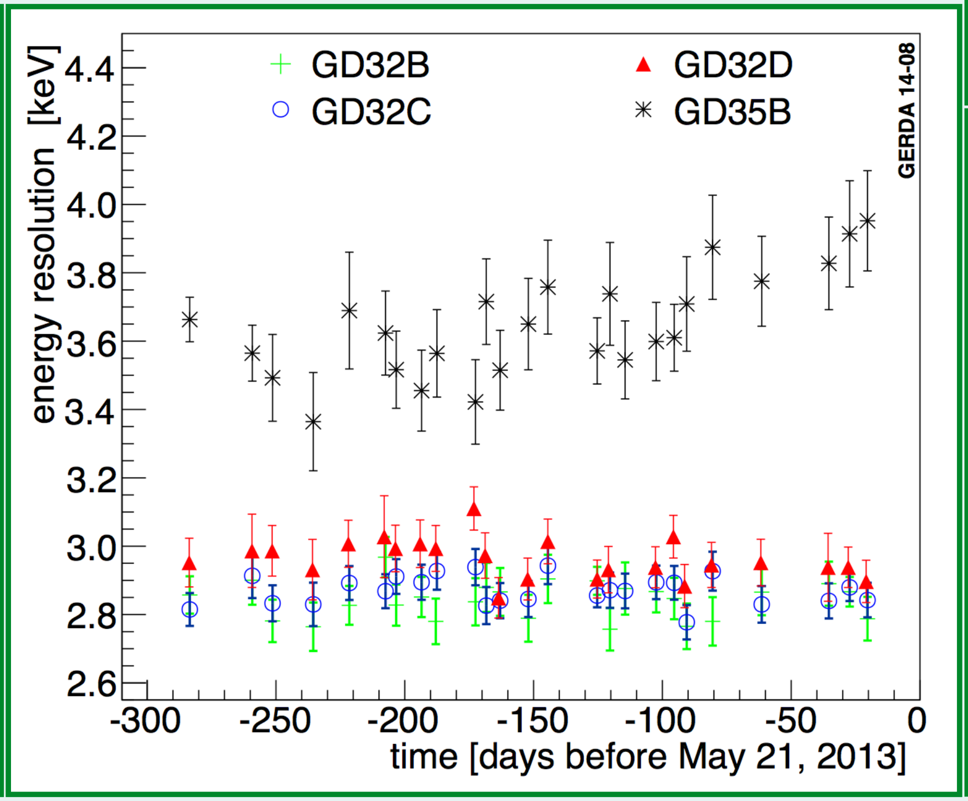
- not due to:
  - set-up related artefacts
  - electronic components
  - noise effects and time instabilities
  - macroscopic properties
    (crystal, impurities, operational voltage…)
- **possibly due to deposition of positive charged compounds in the groove, distorting the E field**
- **groove chemical treatment & thermal heating improves PSD behaviour**

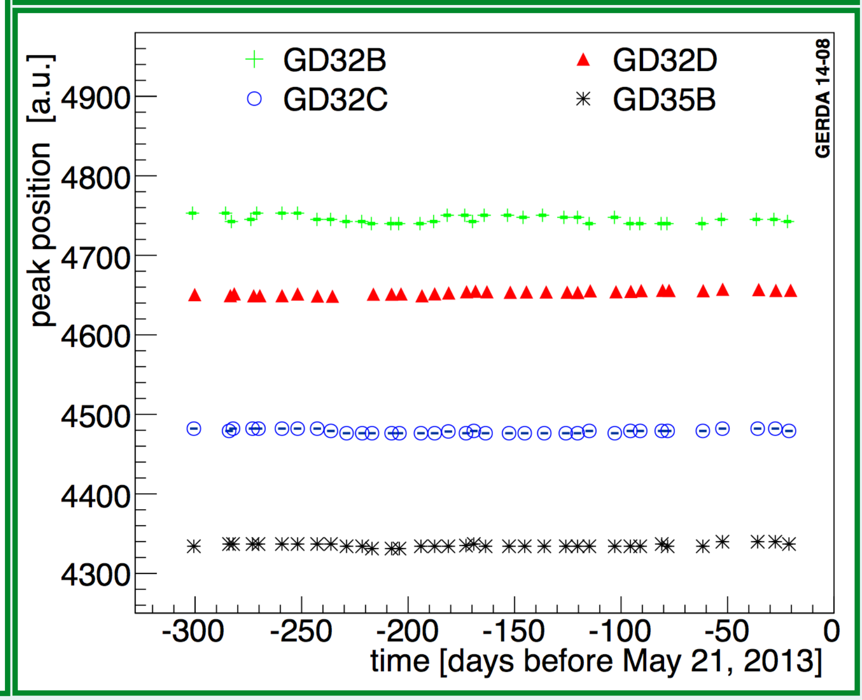
Liquid Argon tests
Phase I BEGe's

- leakage current stable
- stable energy resolution (2.8-3 keV except GD35B)
- resolution ~30% worse than in vacuum
  (longer cable between readout electrode and FET)
- ~30% better resolution than semi-coaxial
- ^{208}Tl γ-peak position at 2615 keV stable within 0.1%



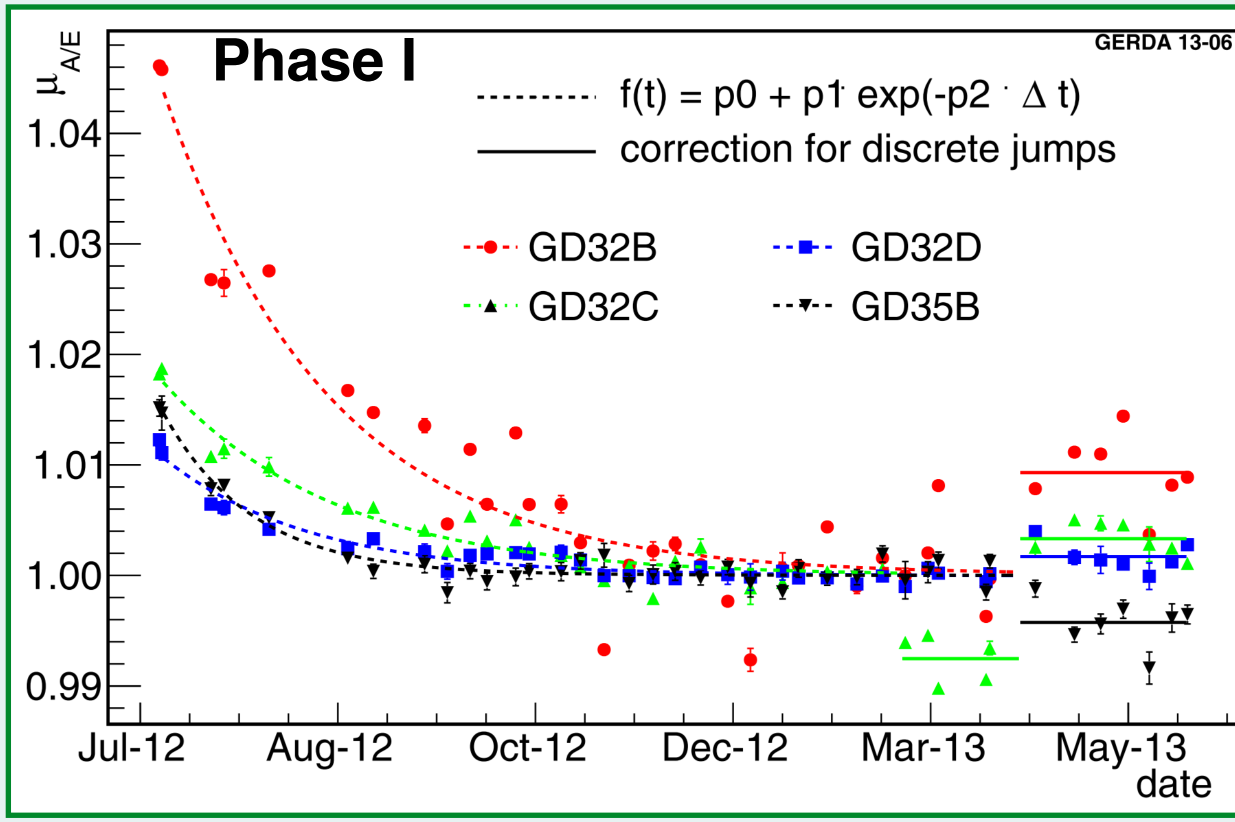




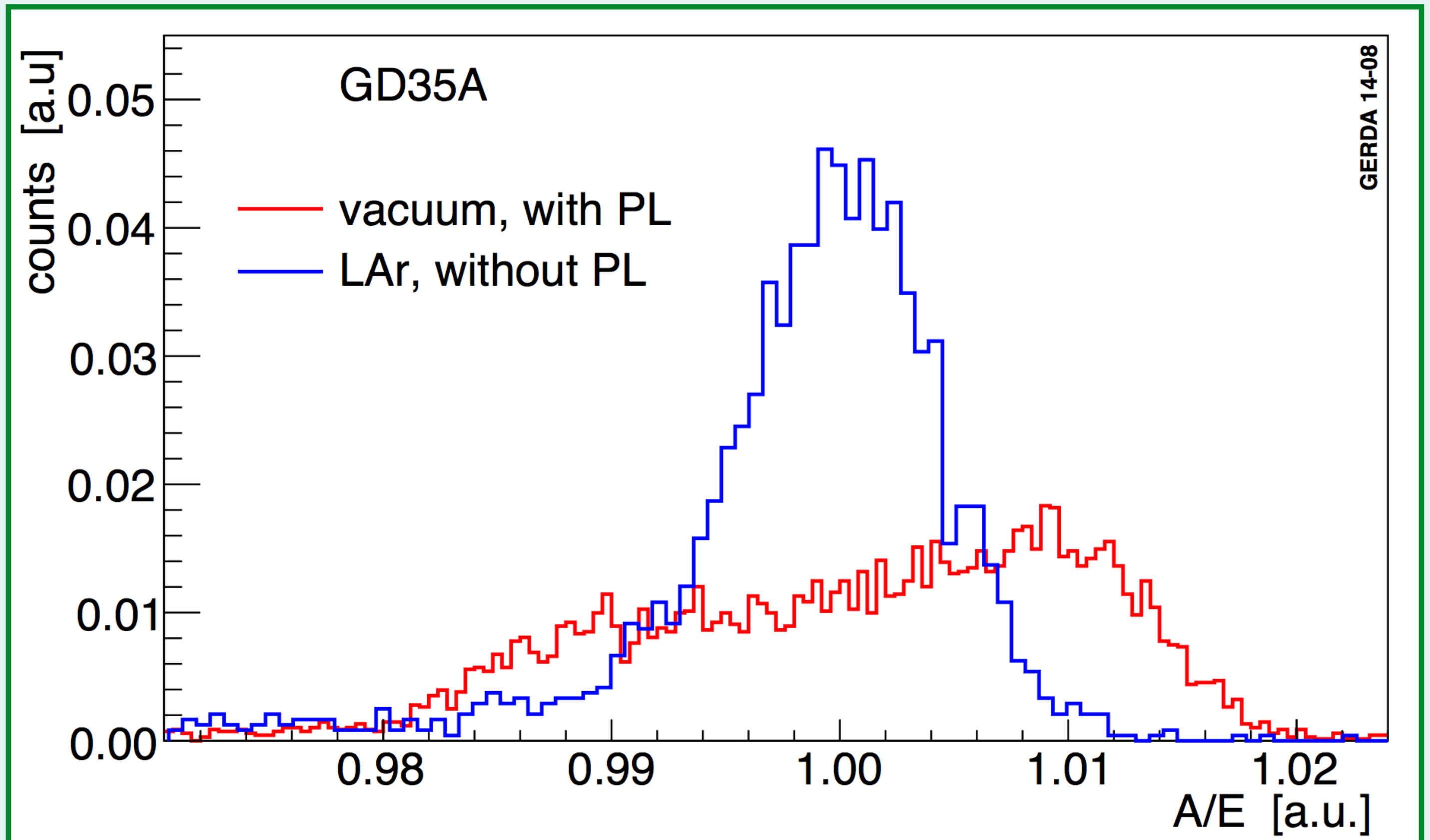


Liquid Argon tests
Pulse shape performance

- drift of mean μ of A/E distributions
  - exponentially decreasing μ (1-5%)
  - μ increase during calibrations (1%)
- possible origin:
  - collection of charged ions on passivation layer during calibration
  - already present charges neutralise or dissolve in LAr



Eur. Phys. J. C (2013) 73:2583



test in LAr without passivation layer

- worse energy resolution due to longer electrode-FET distance
- improved A/E distribution width
- non-Gaussian features disappear
- improvement of PSD survival efficiencies

Summary

- GERDA Phase I goals were reached
  with well-type unpassivated coaxial detectors
- operating bare Ge detectors in LAr successful
- irradiation induced LC investigated and understood
- 30 new BEGe detectors produced (20 kg)
- careful steps during production to minimise cosmic activation
- new contacting scheme (reduced mass and background)
- improved energy resolution
- effective background recognition with PSD
- anomalies related to PSD understood and treated
- stable operation of BEGe detectors
- Phase II expected background index:
  10^{-3} cts/(keV kg yr)
  exploration of $0\nu\beta\beta$ half-lives above 10^{26} yr