From Ge(Li) detectors to gamma-ray tracking array

The history in a nutshell

- The 1960ties and 70ties: Ge(Li) detectors
- The 80ties: HPGe detector arrays with Compton-Suppression Shields, national collaborations
- The 90ties: EUROBALL – GAMMASPHERE
- Since 2000: Position-sensitive Ge detectors

  MINIBALL, AGATA, GRETA

Jürgen Eberth, University of Cologne

First Position Sensitive Germanium Detectors and Application Workshop
and 17th AGATA Week

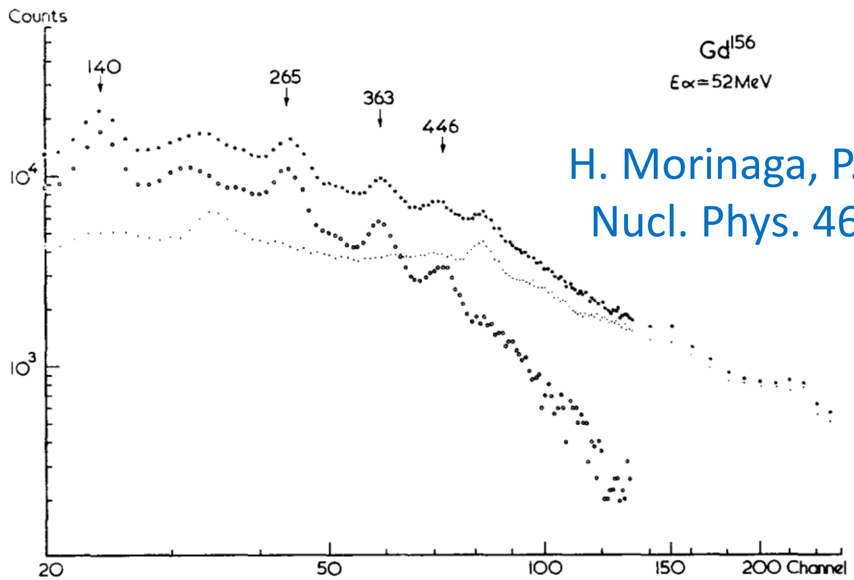
October 3 – 7, 2016 Orsay

Alkali Halide Scintillation Counters

ROBERT HOFSTADTER
Princeton University, Princeton, New Jersey
May 20, 1948

Phys. Rev. 74 (1948) 100

Invention of the NaJ(Tl) detector
1948



(α,xn)

H. Morinaga, P.C. Gugelot
Nucl. Phys. 46 (1963) 210

1947

Ge transistor

by

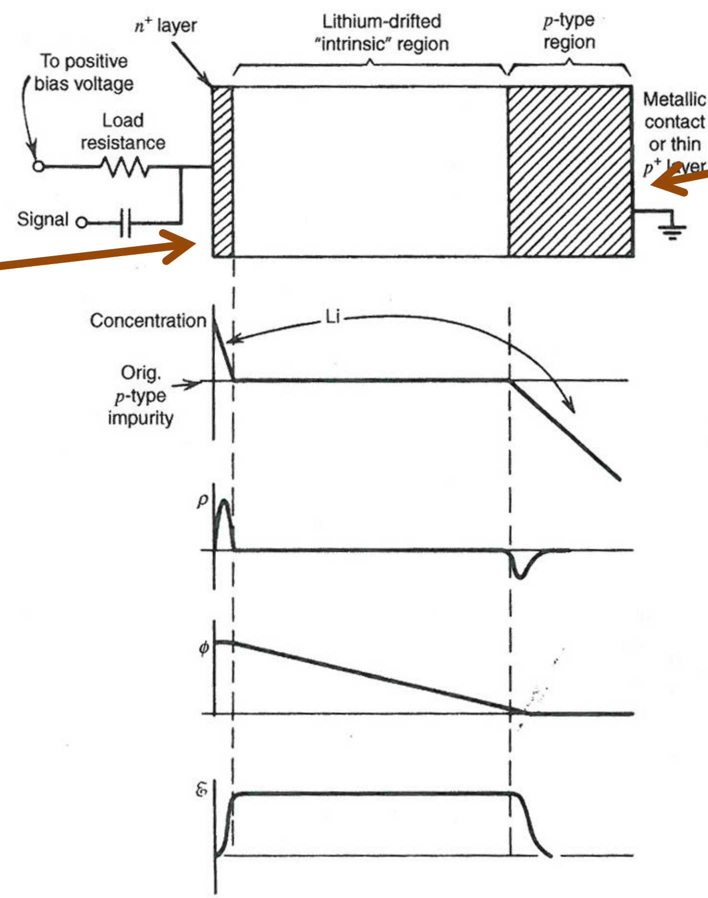
William Shockley,
John Bardeen and
Walter Brattain
(left to right)

JOURNAL OF APPLIED PHYSICS VOLUME 31, NUMBER 2 FEBRUARY, 1960

Ion Drift in an n-p Junction*

E. M. PELL
General Electric Research Laboratory, Schenectady, New York
(Received August 19, 1959)

1960
E.M. Pell



P-type bulk material

Li-diffused n$^+$ layer

Li-drift in p-type Si

First Ge(Li) detector: D.V. Freck and J. Wakefield

Nature 193, 669 (1962)

Ge(Li) detector, active volume: 0.2 ccm

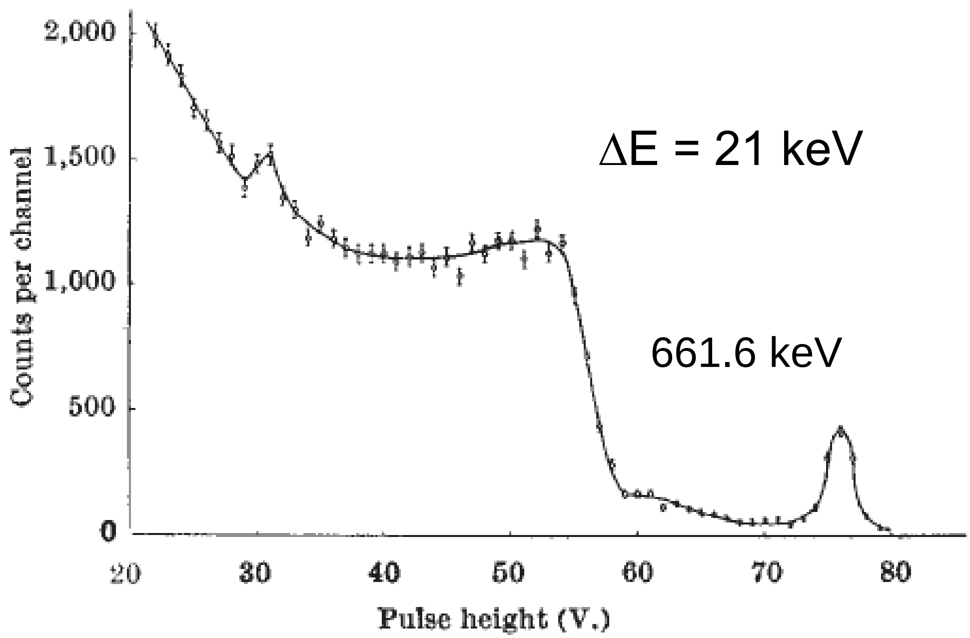


Fig. 1. Pulse-height spectrum from a *p-i-n* junction in germanium due to 663 keV. γ-rays from cæsium-137

NUCLEAR INSTRUMENTS AND METHODS 25 (1963) 185–187; © NORTH-HOLLAND PUBLISHING CO.

A HIGH RESOLUTION LITHIUM-DRIFT GERMANIUM GAMMA-RAY SPECTROMETER

A. J. TAVENDALE* and G. T. EWAN

Chalk River Nuclear Laboratories, Atomic Energy of Canada Limited

Received 14 October 1963

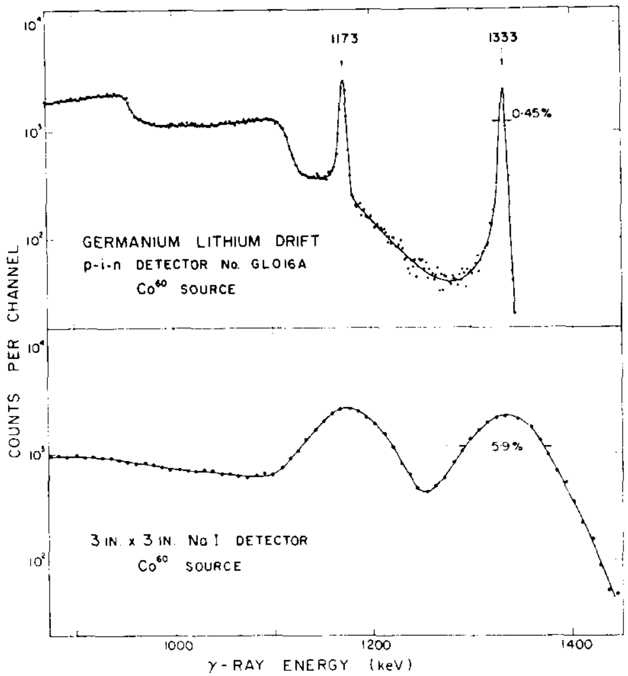


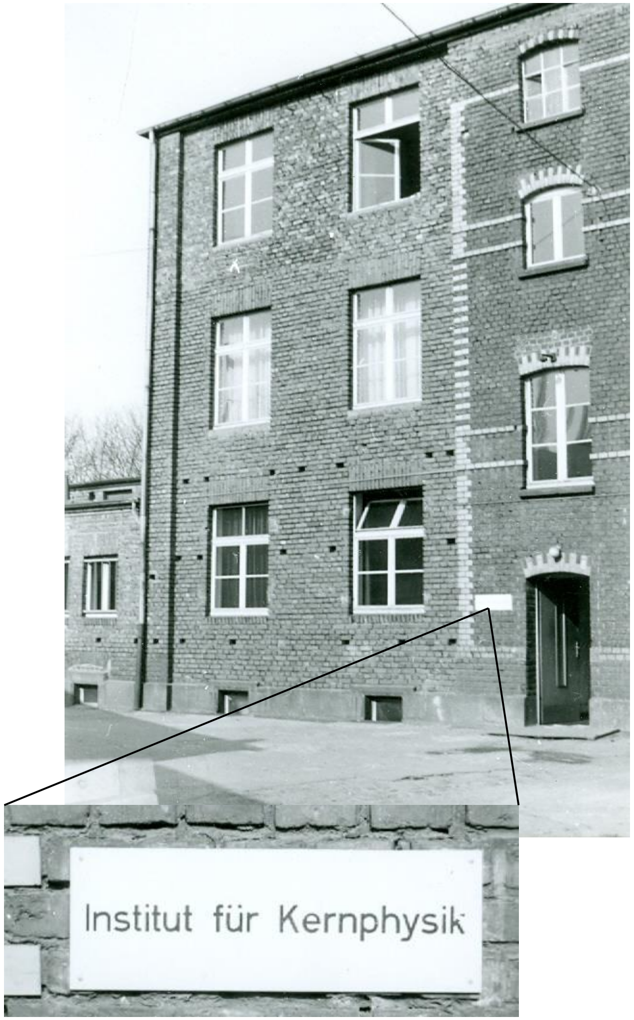
Fig. 1. High energy region of gamma-ray spectrum of Co^{60} observed with the lithium-drift germanium detector. The detector was 18 mm in diameter and had a depletion of 8 mm. It was operated at 77° K with a bias of 450 V across the detector The intrinsic full energy peak efficiency was 0.2 %. The spectrum shown above was obtained in 10 min using a 20 μC Co^{60} source. For comparison we show the same region of the spectrum observed with a good 3″ × 3″ NaI scintillation spectrometer. This spectrometer had a reso'ution of 8.0 % on the 661 keV γ-ray in Ba^{137}.

1963 Tavendale and Ewan (Chalk River)

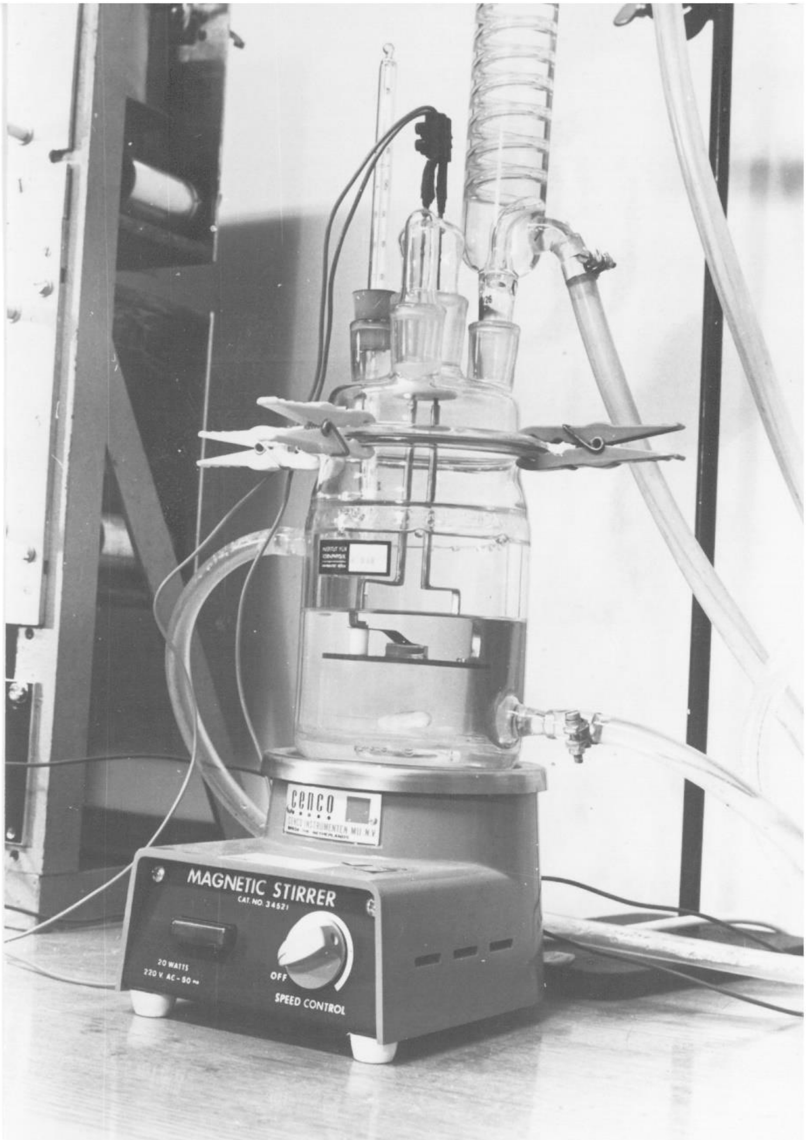
Ge(Li) detector, planar: 2 ccm

ΔE = 6 keV at 1.3 MeV

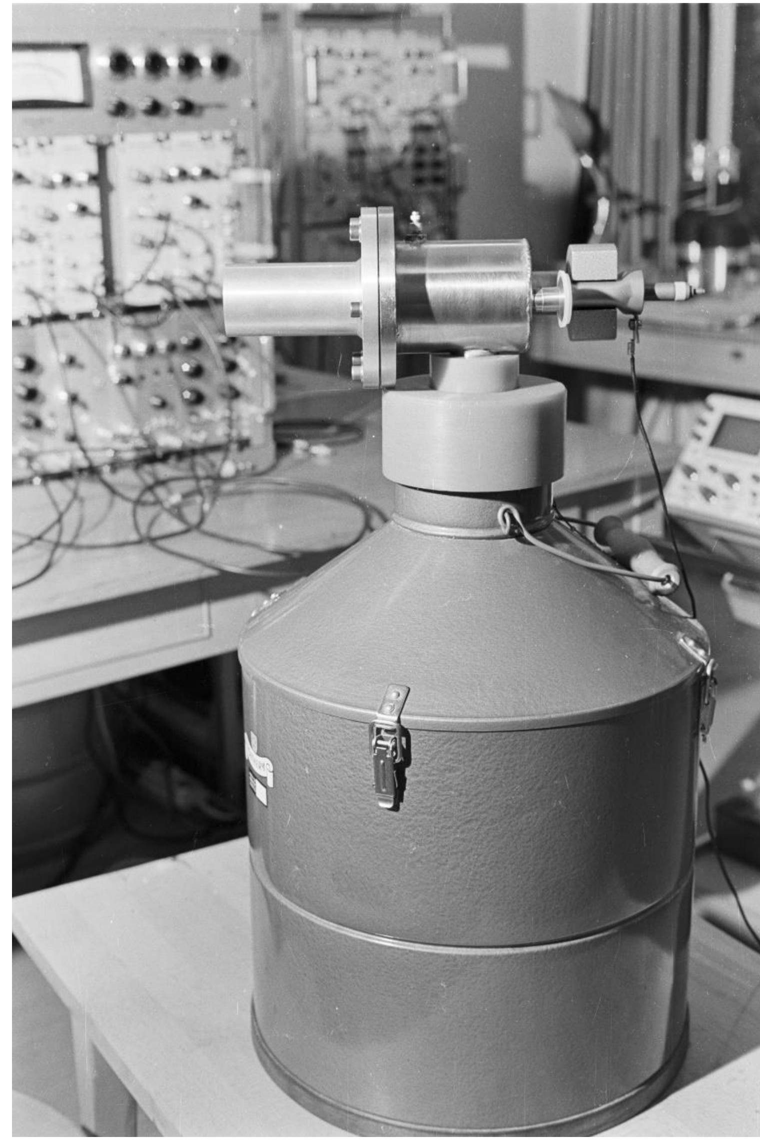
The first building
1960



Installation of the FN-Tandem
in the new building 1967-68

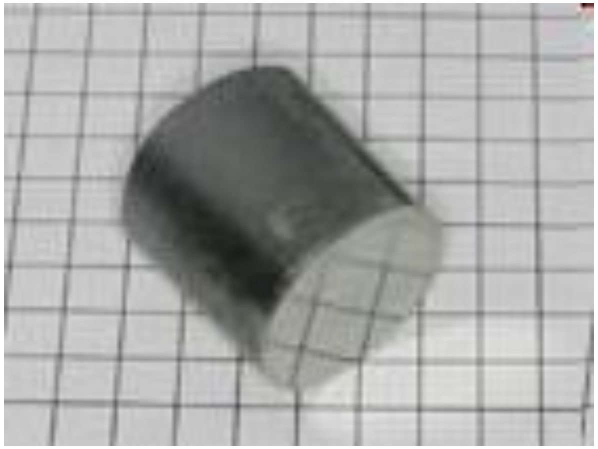


Li-drift apparatus
at IKP Cologne



First coaxial detector 1968
ΔE = 3.5 keV at 1.3 MeV
5.5 ccm

The 1970ties



γ-spectroscopy with Ge(Li) detector
10 -15 % rel. Efficiency (Vol. 50-70 ccm)
Resolution 1.9 – 2.3 keV at 1.3 MeV

But also first segmented and composite detectors

The „five-in-one“ Compton Polarimeter (1974)

E. Eube et al., NIM 130 (1975) 73

Two concentric coaxial Ge(Li) detectors, outer detector 4-fold segmented

energy resolution 3.5 – 5 keV at 1.3 MeV

Crystal: 65 mm diam.
46 mm long
153 cm^3

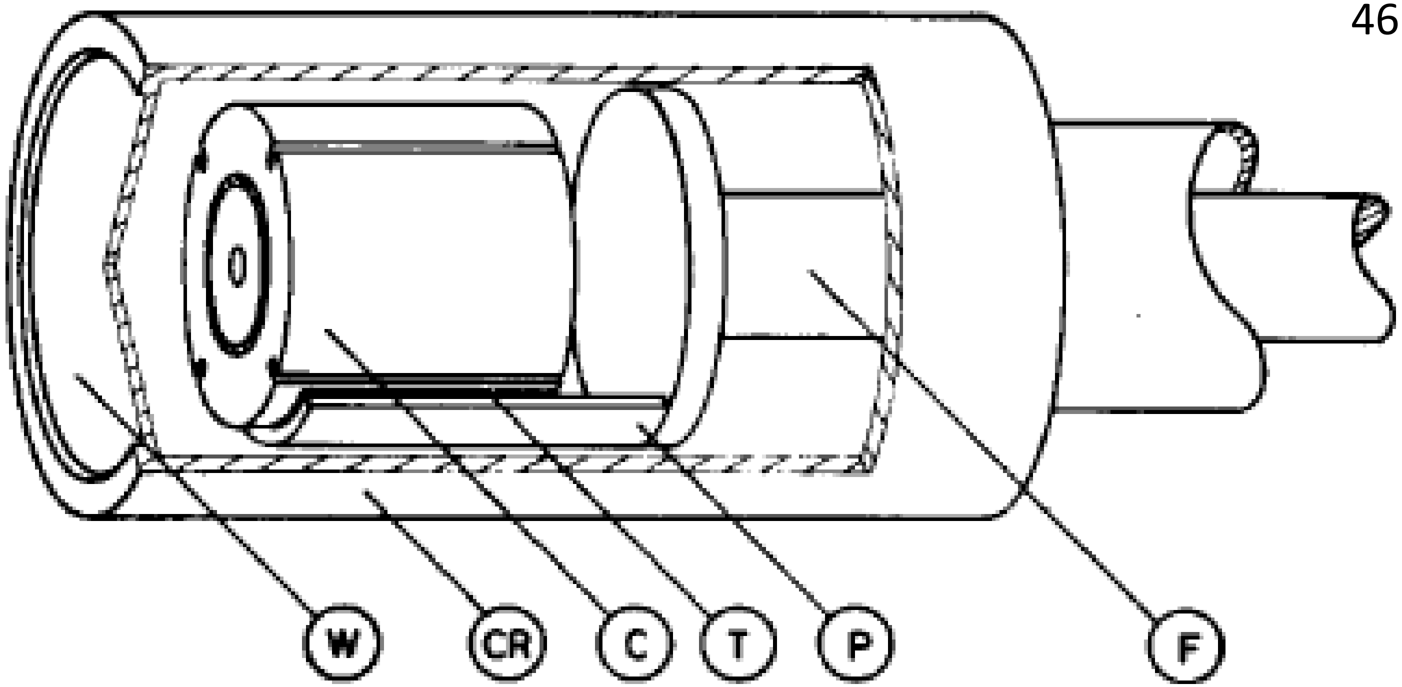


Fig. 1. Cross section of the polarimeter. W = thin window, CR = cryostat, C = crystal, T = Teflon insulation, P = crystal holder, F = cold finger.

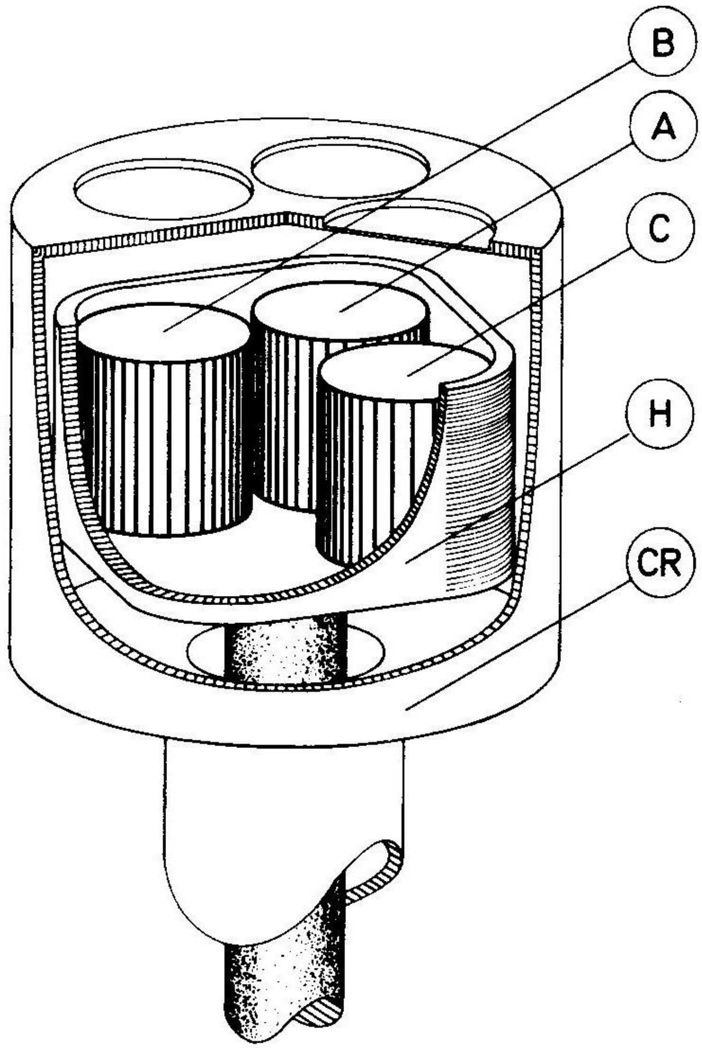


FIG. 4. Three-crystal Compton polarimeter, Detector A acts as scatterer, the absorbers B and C are shielded from direct radiation by a 4 cm collimator of Densimed (see text). CR = cryostat, H = heat shielding.

Composite Ge Detectors

3(4) Ge(Li) detectors
in a common cryostat

(1976)

resolution 2.1 keV at 1.3 MeV

for 3 but not for 4 detectors

Encapsulation ?

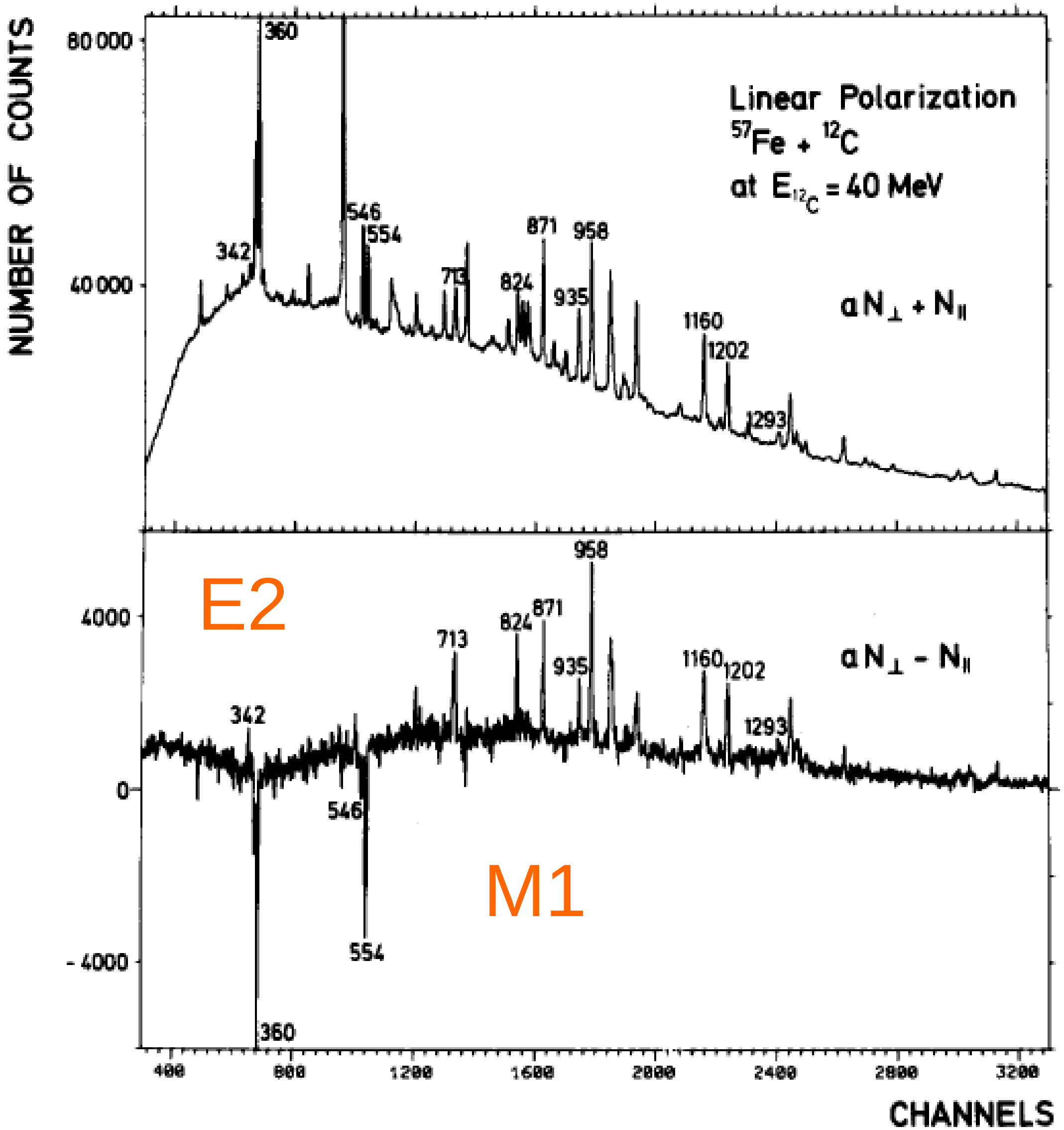


Fig. 7. Sum and difference spectra from the linear polarization measurement. Transitions in ^{67}Ga are labelled with their energy in keV.

^{67}Ga

linear polarisation

V. Zobel et al.
1978

The Berkeley High-Purity Ge Team

Milestone 2

ERDA NEWS September 19, 1977

for the Ad-
s Review at

vill speak on
t the 5th An-
nference in

ational War
ssues (Wash-
Cantus, Di-
lations, will
Harvey Lyon,
Security, will
oliferation.

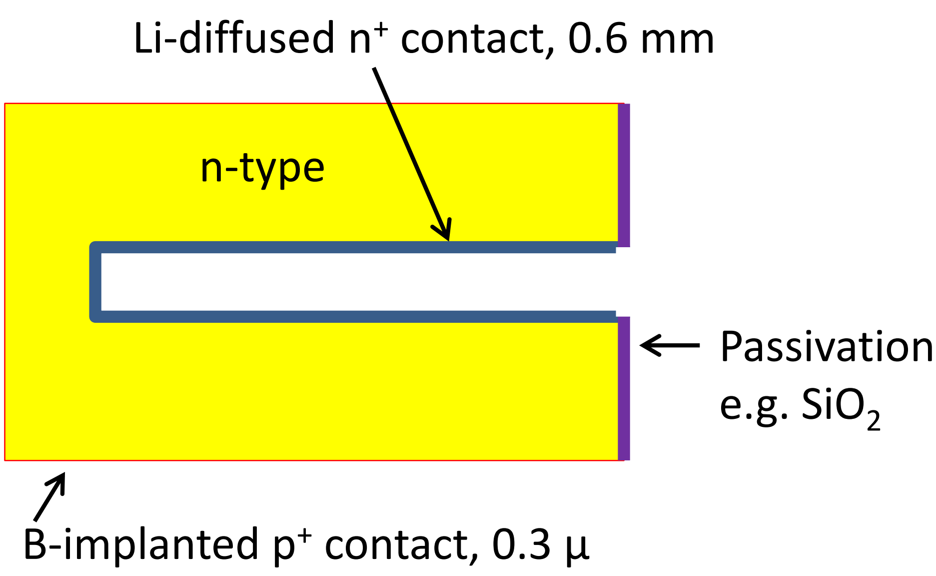
Affairs Nel-
te in a meet-
Institute for
n Laxenburg,

iclear Energy
t in a Confer-
&D Manage-

PURE AND COSTLY—Lawrence Berkeley Lab scientists (l-r) William Hansen, Eugene Haller and Scott Hubbard gaze at a germanium crystal worth about $15,000. Purified germanium has scientific applications in archeological dating, geological and chemical analysis, nuclear chemistry, physics and medicine. (LBL Photo)

High Purity Germanium detector

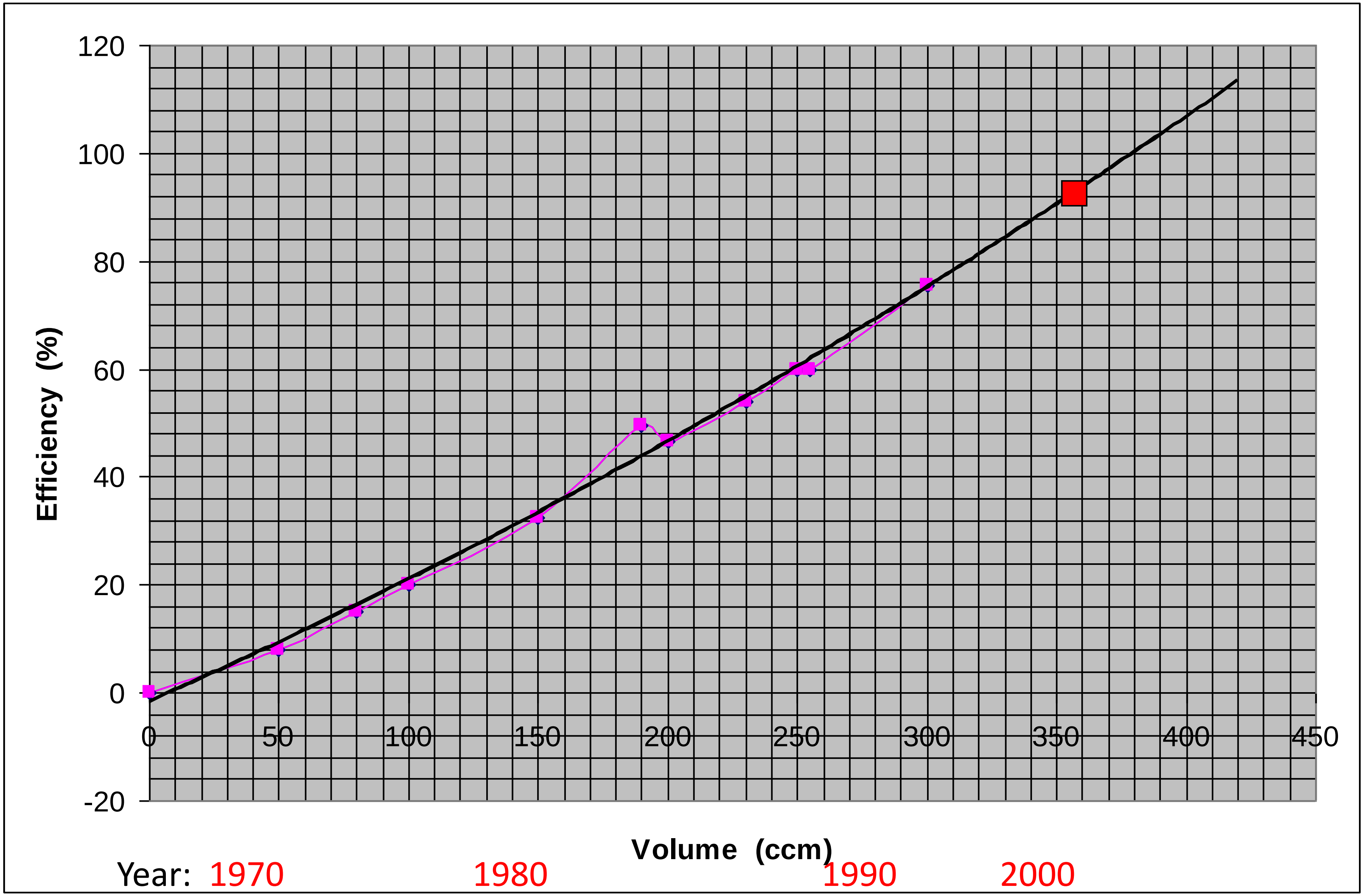
n-type Germanium with impurity concentration of $5 \times 10^9 - 2 \times 10^{10}$ / cm^3
Producer: e.g. UMICORE



The way to optimize a Ge detector array for in-beam γ-ray spectroscopy

Aim: Study rare γ-rays emitted from recoiling nuclei

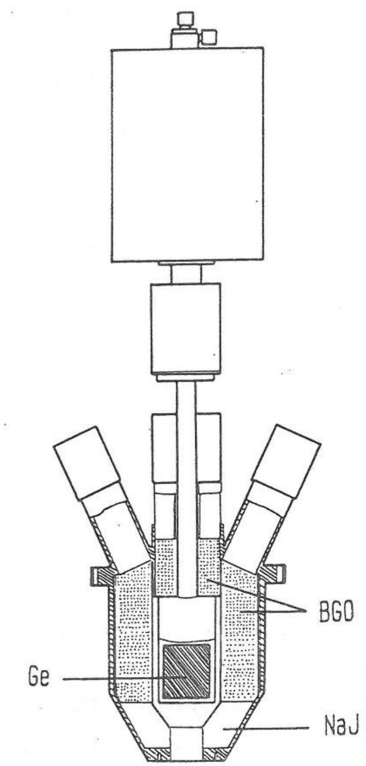
Energy resolution:	2 keV at 1.3 MeV
Efficiency:	large detectors, maximize the amount of Ge
P/T:	large detectors, BGO escape suppression shields
Doppler correction:	small solid angle of γ-detection, high granularity
High-fold γ-coincidences:	high granularity of the array for good isolated hit probability



AGATA Detector: Volume 355 ccm, Eff. 90 %

The 1980ties

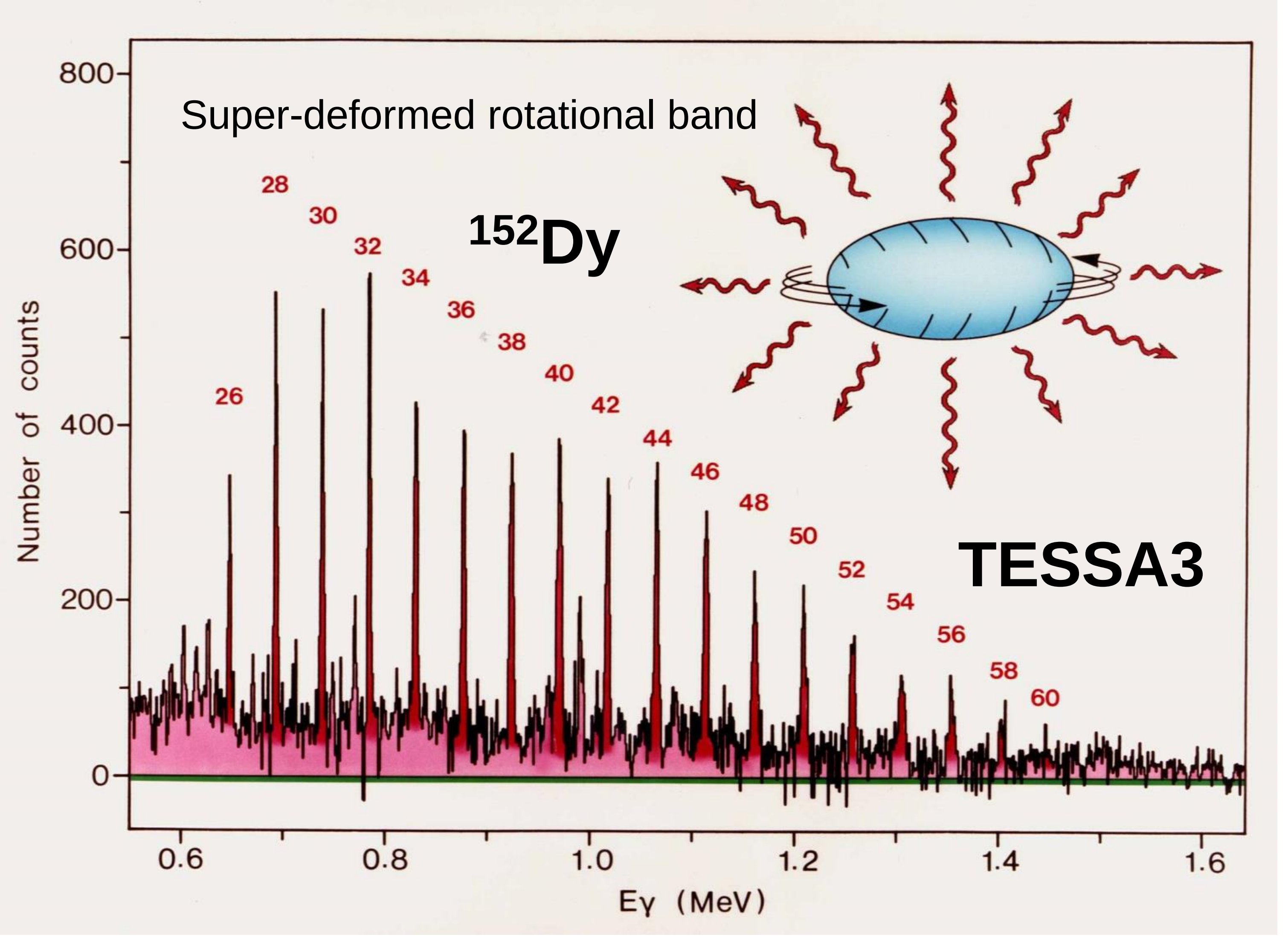
Home-production of Ge(Li)‘s was abandoned after 1978 when high-purity Ge (HPGe) detectors became commercially available



Detector arrays with HPGe detectors
and
BGO escape suppression shields by
national collaborations

TESSA Daresbury (5-16), HERA Berkeley (21),
OSIRIS Cologne Berlin (12), NORDBALL Kopenhagen (20),
Chateau de Cristal Strasbourg (12),
8π Spectrometer Chalk River (20), GASP Legnaro (40)

Impact of the arrays on nuclear structure physics: Isolation of rare excitations by γ-γ-γ-coincidences



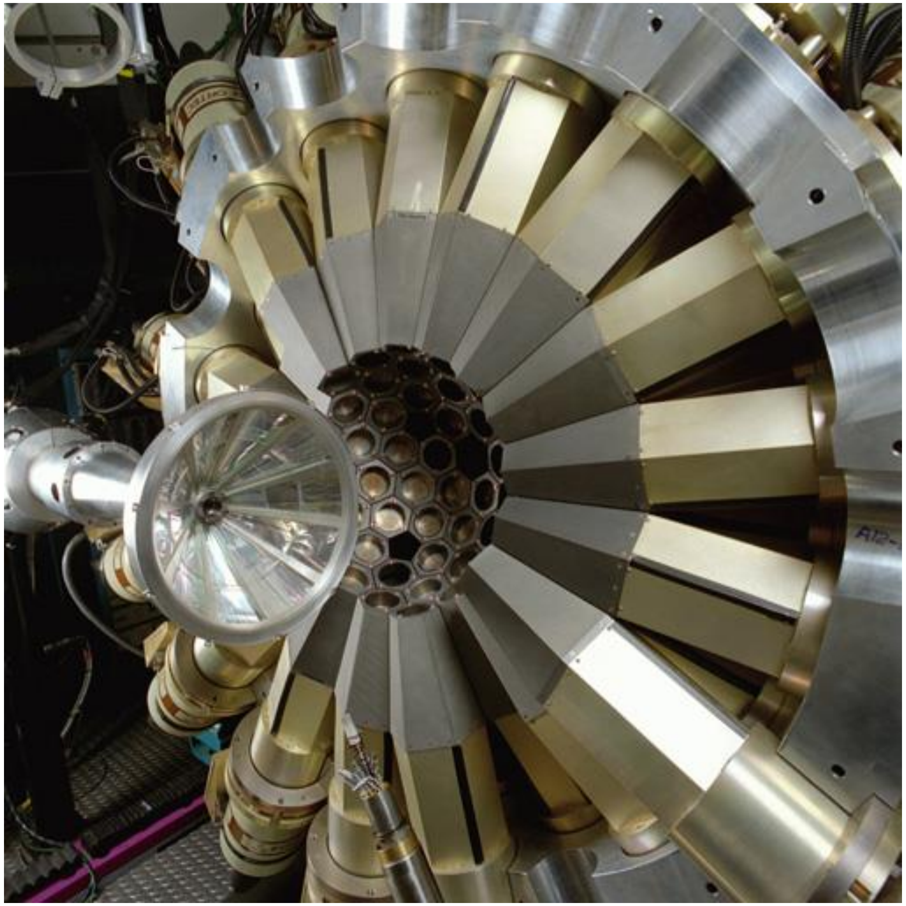
P.J. Twin et al., Phys. Rev. Lett. 57(1986)811

GAMMASPHERE

Berkeley, Argonne

1993 – 1996

abs. efficiency ≈ 10 %



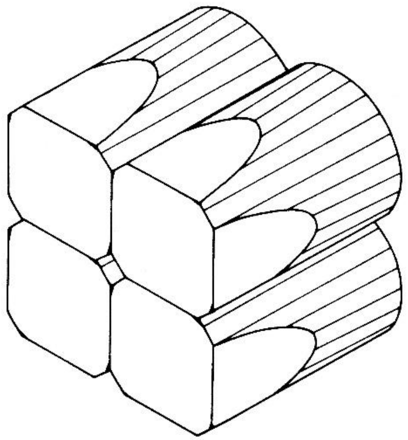
110 escape suppressed Ge detectors of

(70 detectors segmented into two halves)

70% efficiency

M.A. Deleplanque, R.M. Diamond eds.
Gammasphere Proposal (1987)

24 Clover Detector



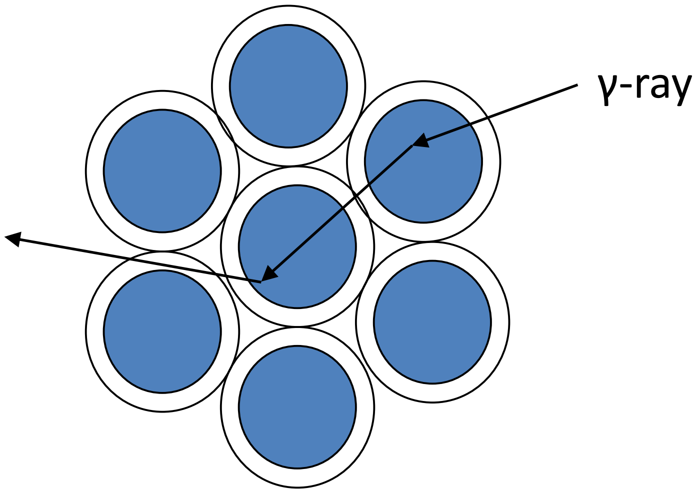
improved eff. by add-back
better Doppler correction
linear polarization

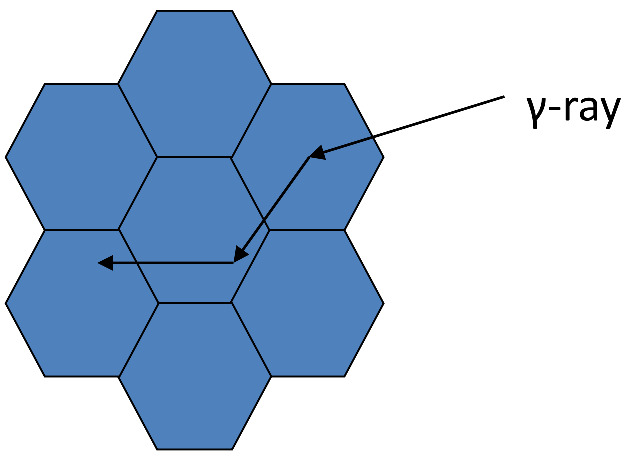
F.A. Beck, G. Duchene

EUROGAM II
french-british collaboration

abs. eff. 8.1%

The EUROBALL Cluster Detector





Late 1980‘s :

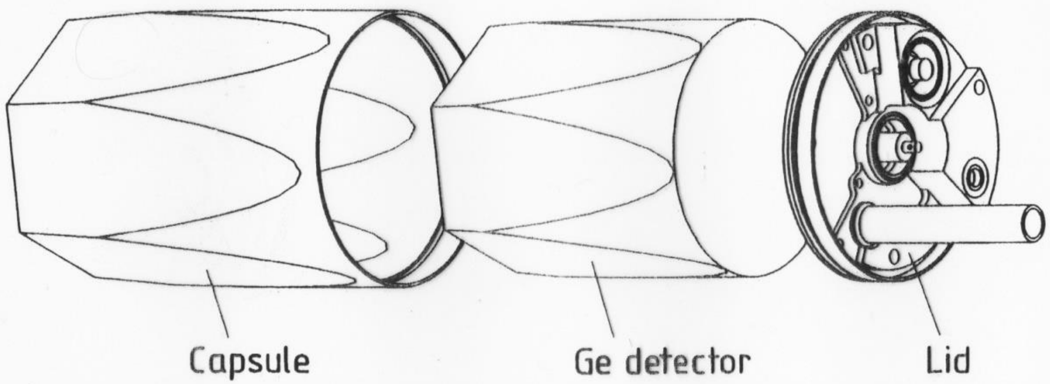
Discussion of a cluster of seven detectors with large efficiency in add-back mode

Conclusion:
seven hexagonal detectors in a common cryostat

Encapsulation !

The encapsulated Ge detector

capsule and lid sealed by electron-beam welding
internal Getter, vacuum < 10^{-6} mb,
temperature range -196 ^{0}C and +110 ^{0}C



Collaboration: Köln, Jülich, Eurisys

J. Eberth et al., NIM A369 (1996) 135

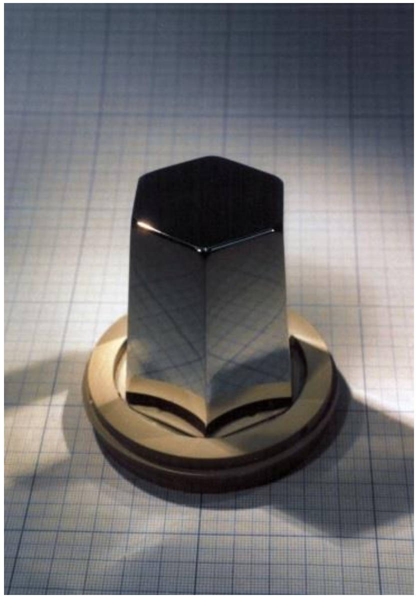


Fig. 4 *Photograph of* the *first hexa-gonal tapered* Ge *detector.*

The development of a first hexagonal **tapered** Ge detector was finished success fully. Intertechnique in **a** first step produced **a standard ooaxial** n-type detector of 60 mm diameter and 70 mm length which was tested with respect to energy resolution and timing properties. Then. this crystal was grinded to the hexagonal tapered
Shape, front diameter 48.5 mm, end dia meter 58.9 mm, length 68 mm>. This two step procedure was chosen to distinguish between crystal properties and the influence of the hexagonal **shape.**

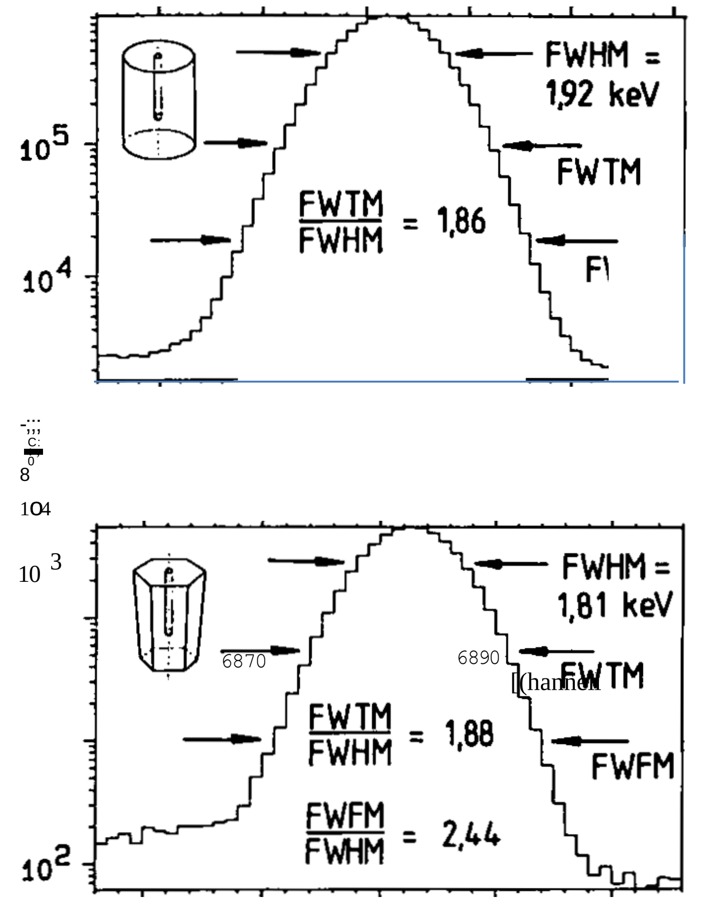
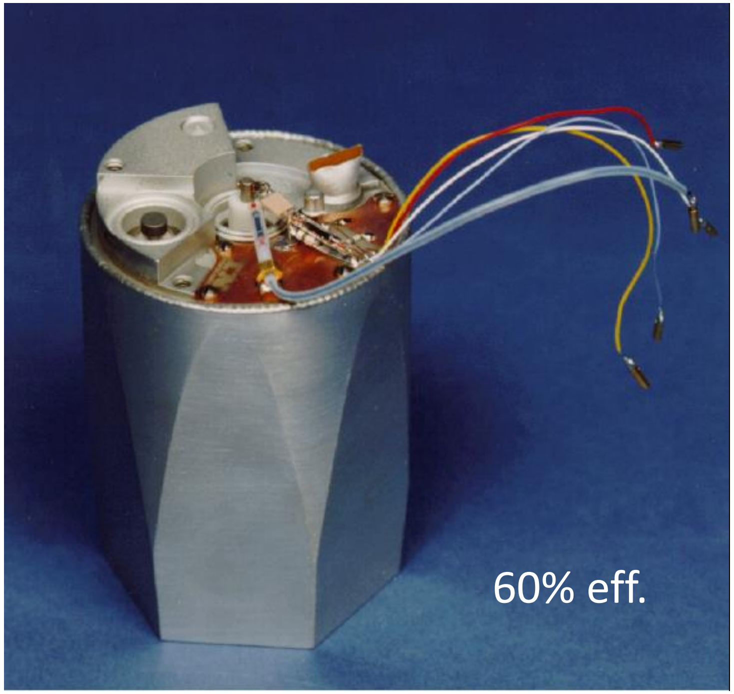
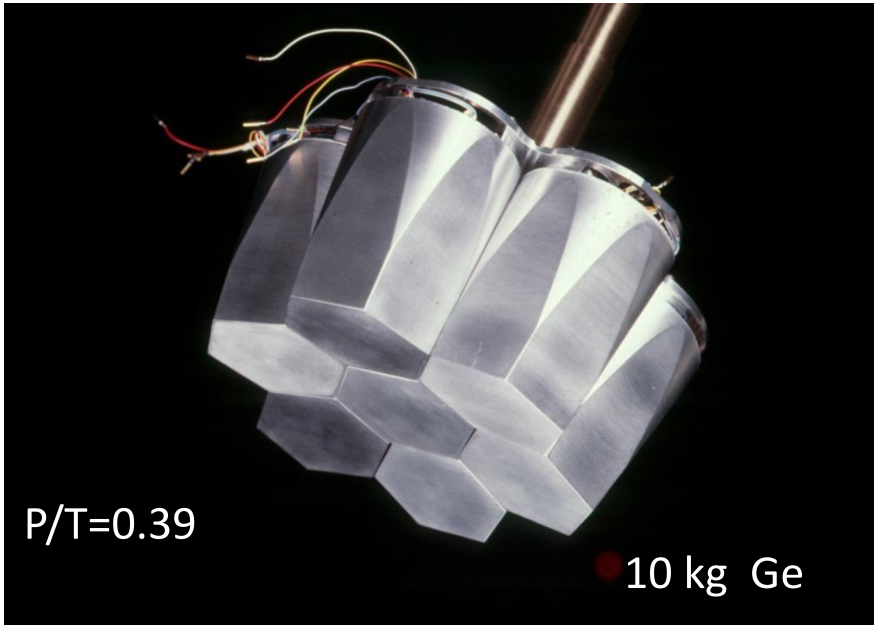
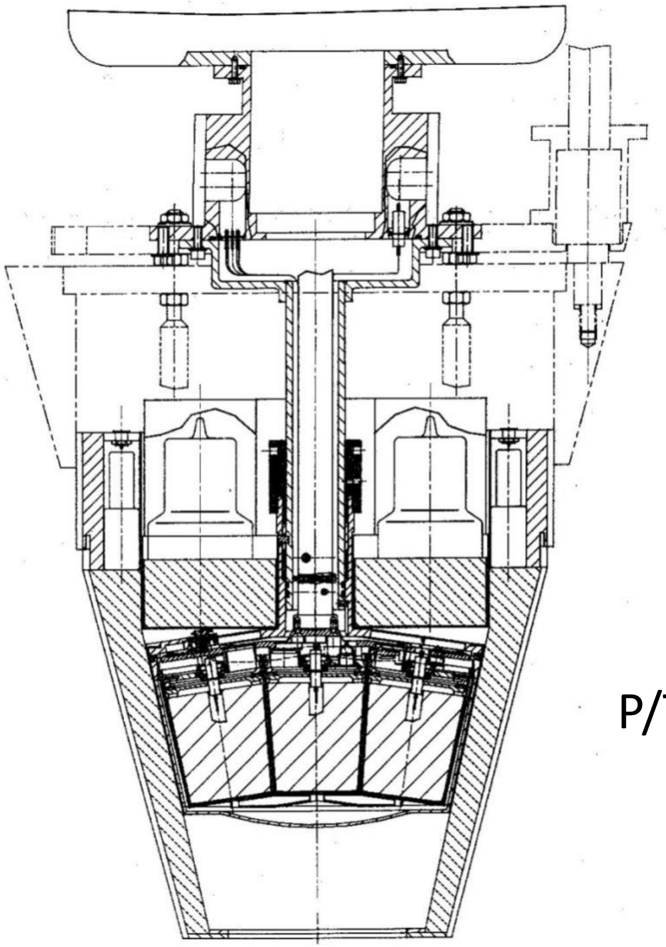


Fig.5 *Comparison of* the *energy resolution and* the *line shape of the 1332.5* ke *V* · *60co* line *for a coaxial detector (upper parV and* ***a*** *hexagonal fapered detector Gower parV* made *from the* sarne *Ge crystal.*





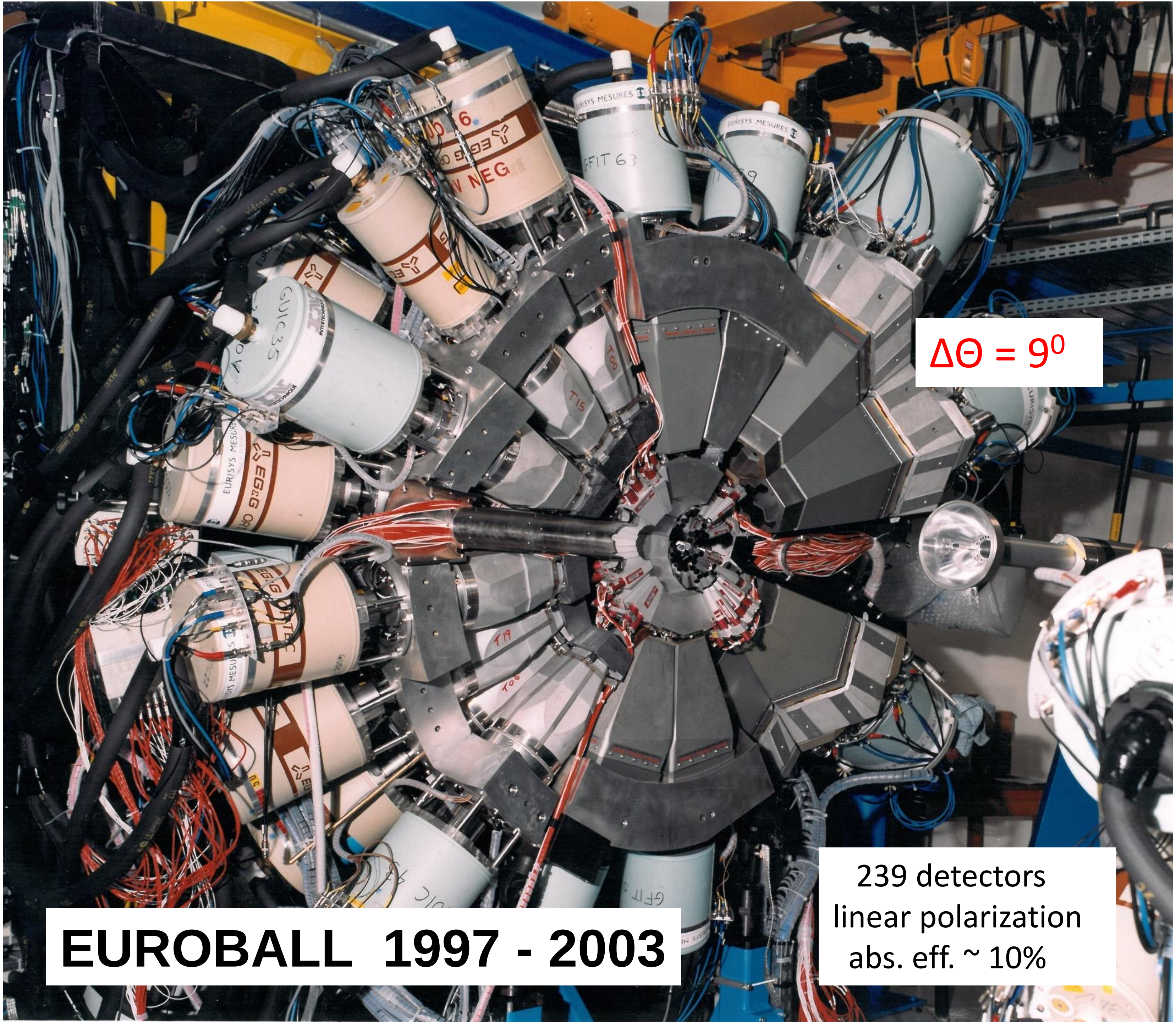
H.G. Thomas Ph.D. thesis



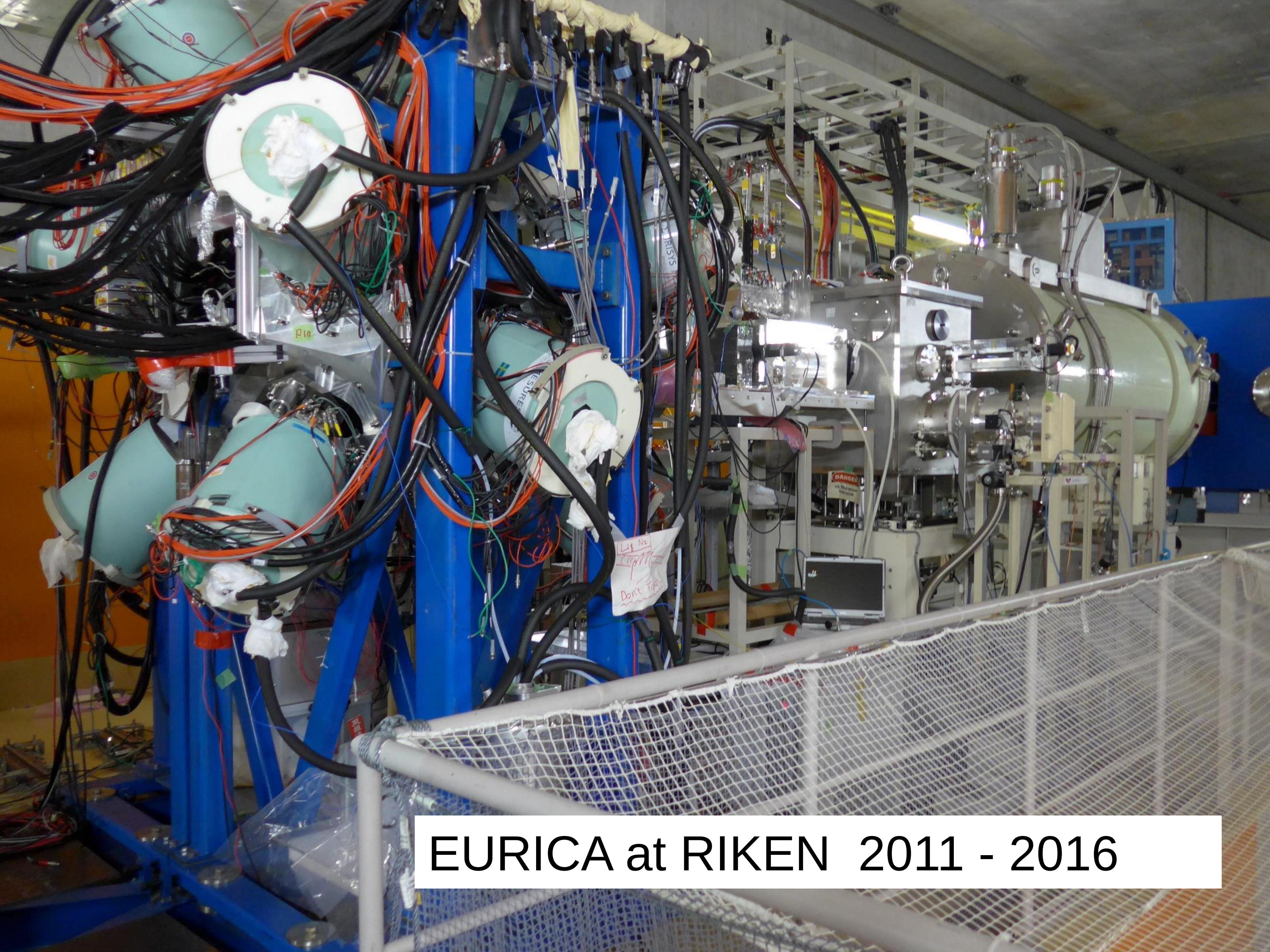
P/T=0.6

The EUROBALL Cluster Detector

1992


ΔΘ = 9⁰
239 detectors
linear polarization
abs. eff. ~ 10%
EUROBALL 1997 - 2003

RISING at GSI 2003 - 2011



EURICA at RIKEN 2011 - 2016

Radioactive Ion Beams

New challenge for the gamma-ray array

Very low beam intensities

→ Need high efficiency

→ 4π geometry of the Ge detectors like EUROBALL

Inverse kinematics

→ Leads to large Doppler broadening

→ Detector should subtend small solid angle

→ Need high granularity

Answer: Position-sensitive Ge detectors

Position-sensitivity of Ge detectors is based on:

- Segmentation of the detector contacts
- Signal processing with digital electronics
- Pulse shape analysis

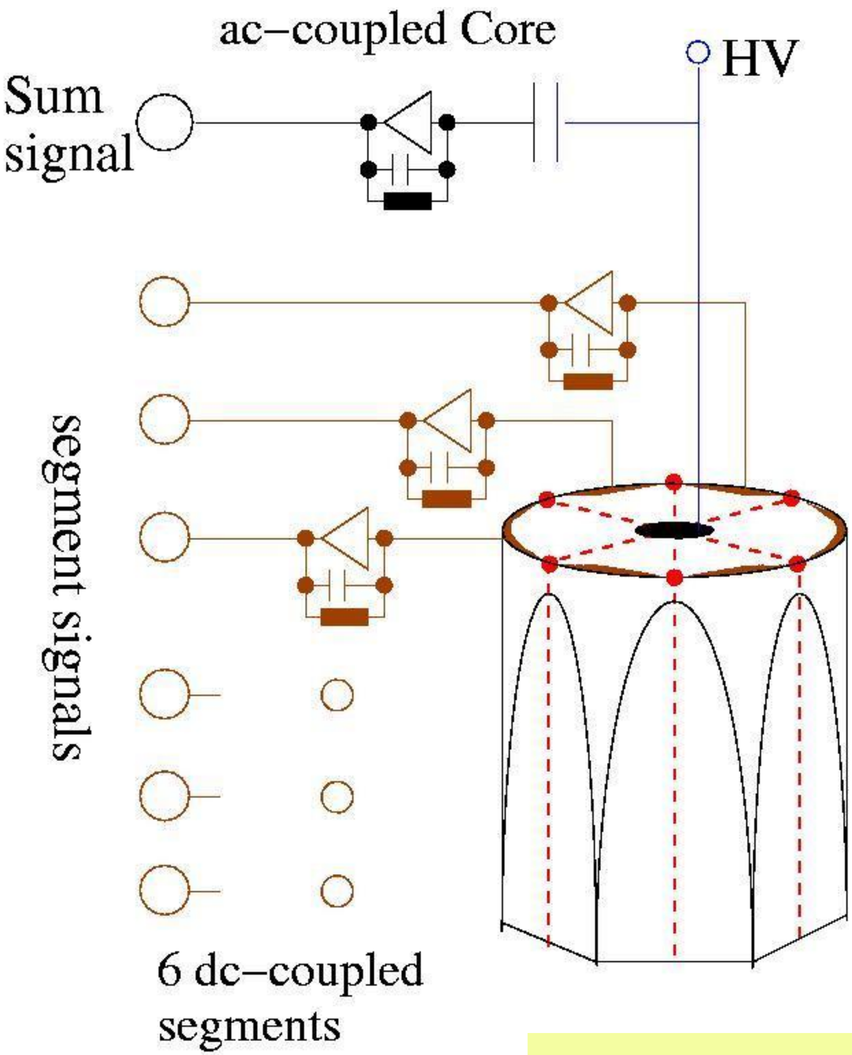
Milestone 3

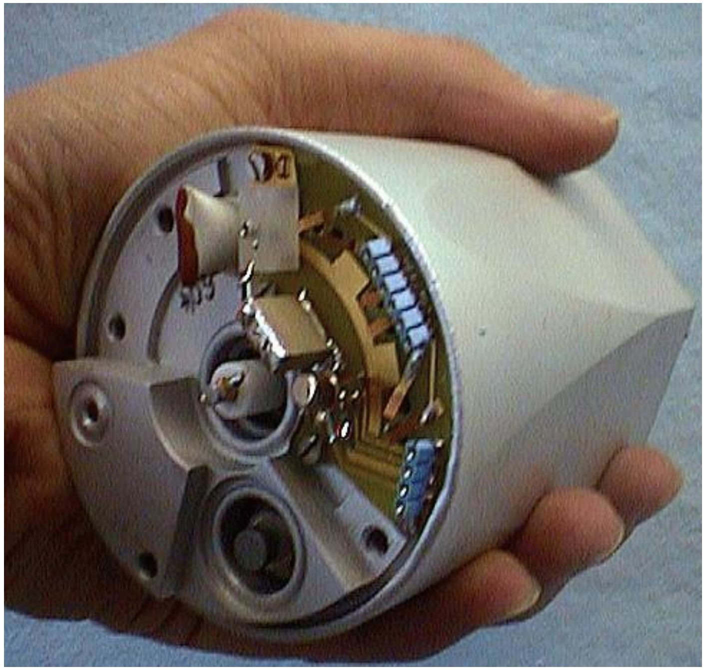
Segmented detectors: **SEGA, EXOGAM, TIGRESS**

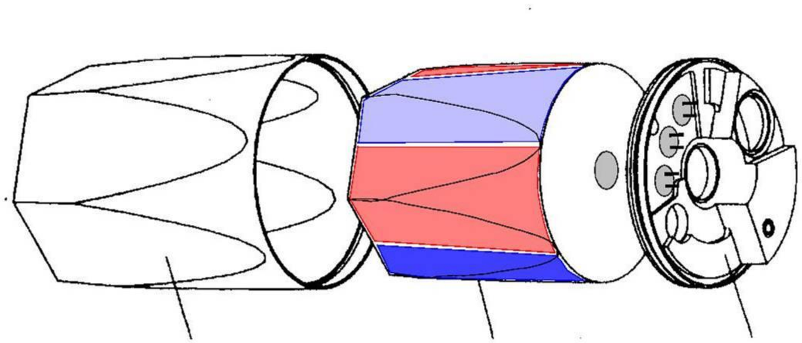
MINIBALL at REX-ISOLDE:

The first array with segmented detectors
and digital signal processing

The 6-fold segmented, encapsulated MINIBALL detector



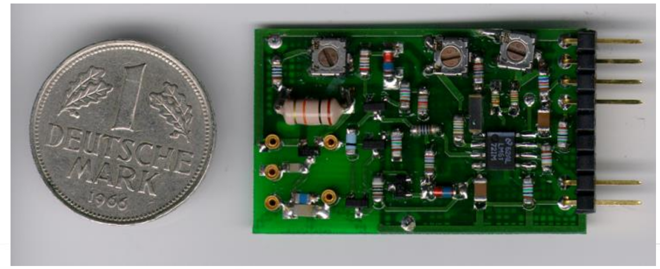




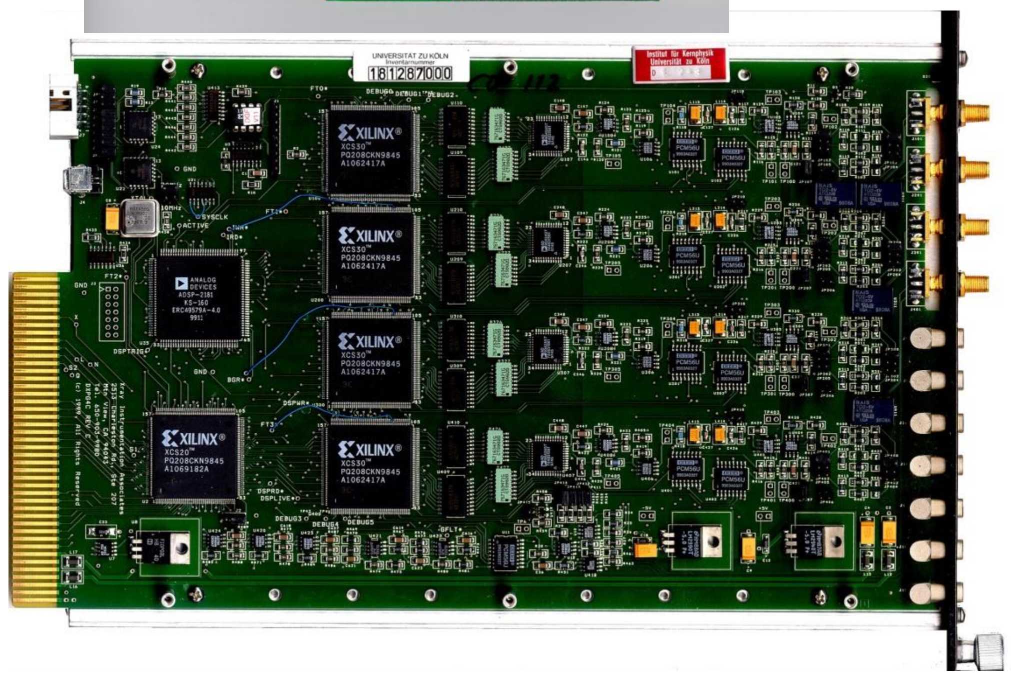
Collaboration: Köln, Heidelberg, München, Leuven

MINIBALL components

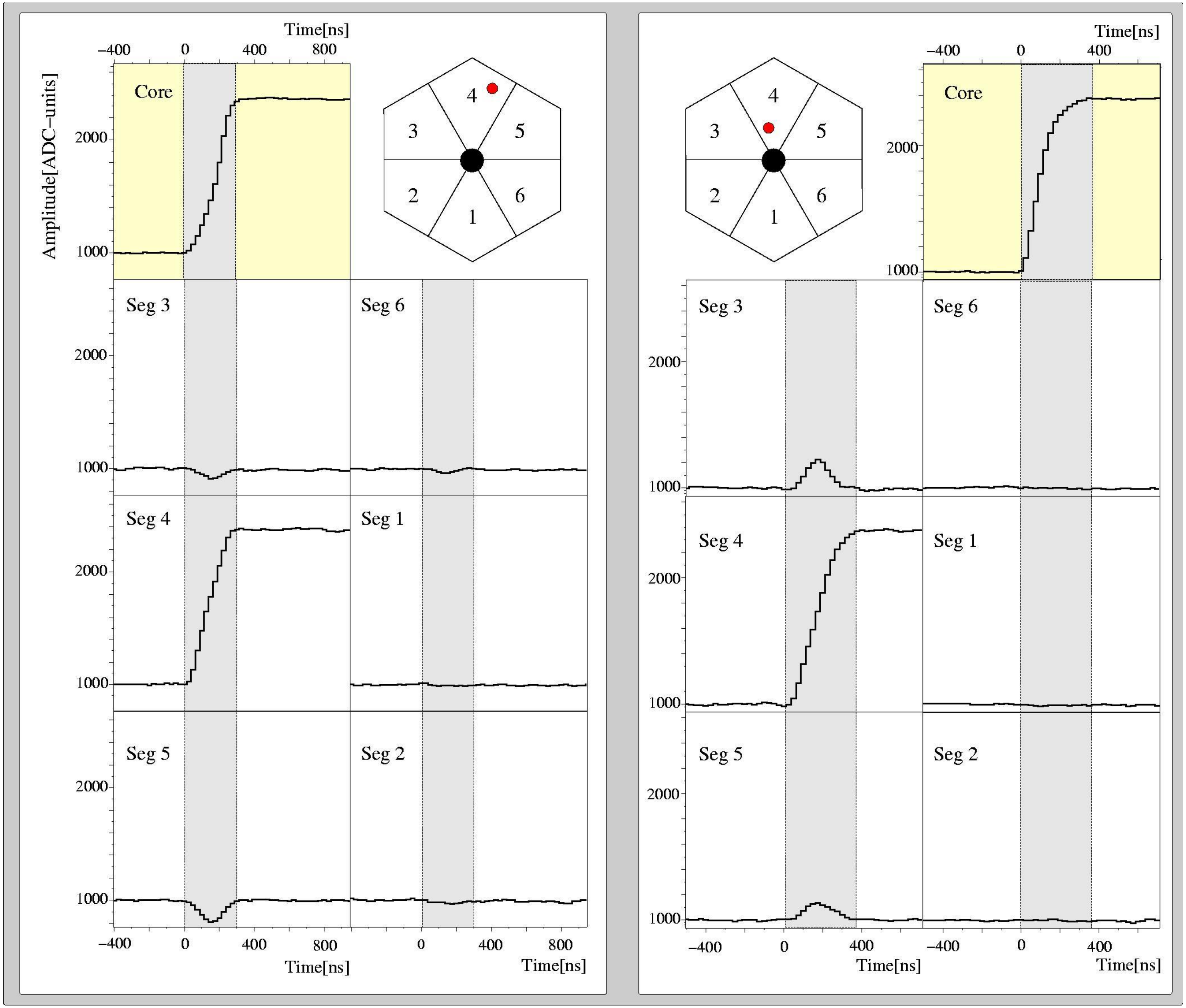
IKP Köln and CTT



Preamp.
IKP Köln
MPI-K Hd



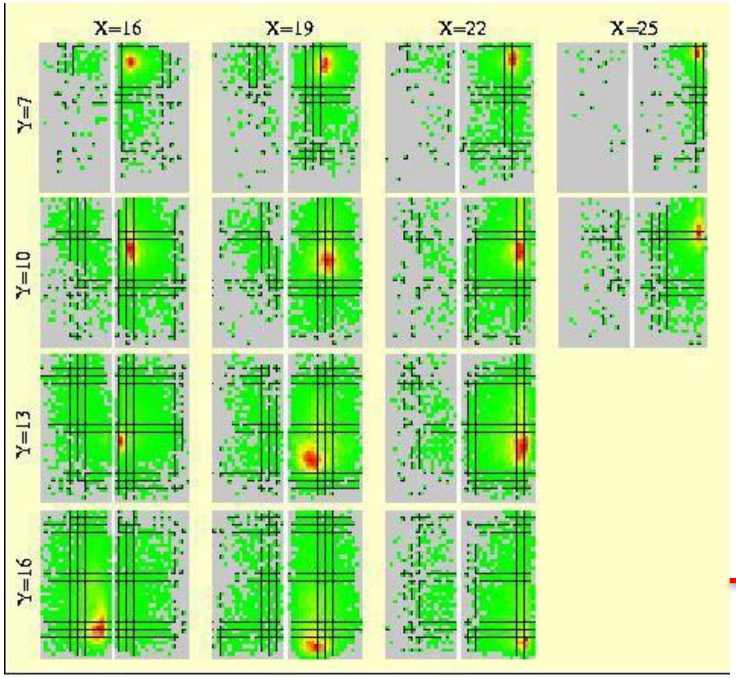
40 MHz digitizer: DGF 4C: Company XIA

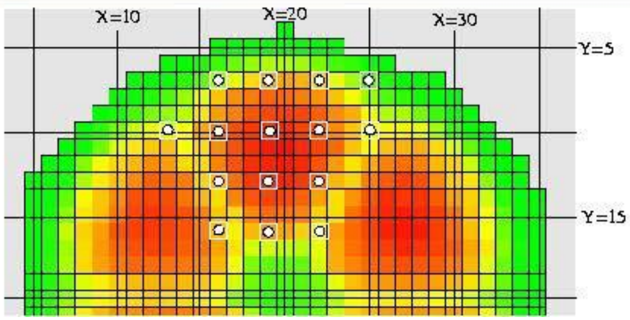


For PSA, we assume: main interaction is first interaction

D. Weißhaar, Ph.D. thesis

Scan of a MINIBALL detector with a collimated ^{137}Cs source





Pulse shape analysis:
Time to steepest slope vs. asymmetry of mirror charges

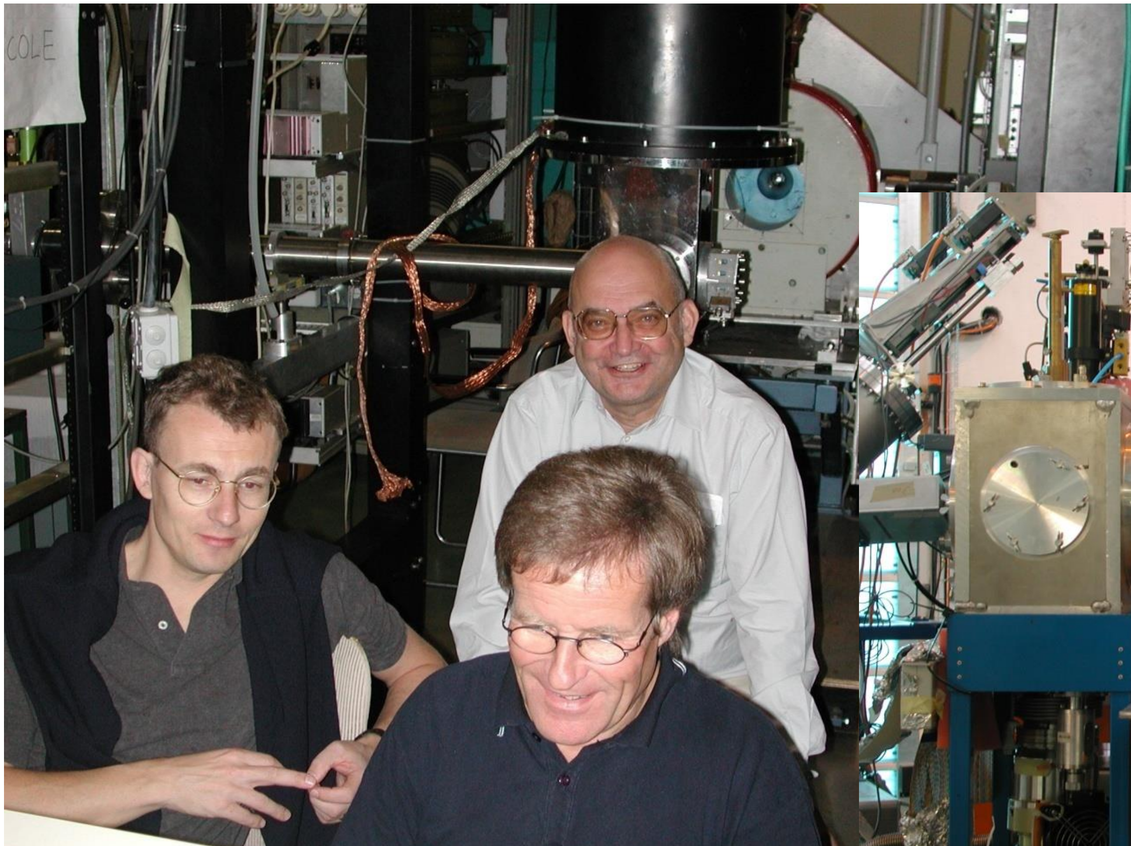
Distinguish between 16 collimator postions/segment

→ Granularity of a MINIBALL detector
6 x 16 = 96

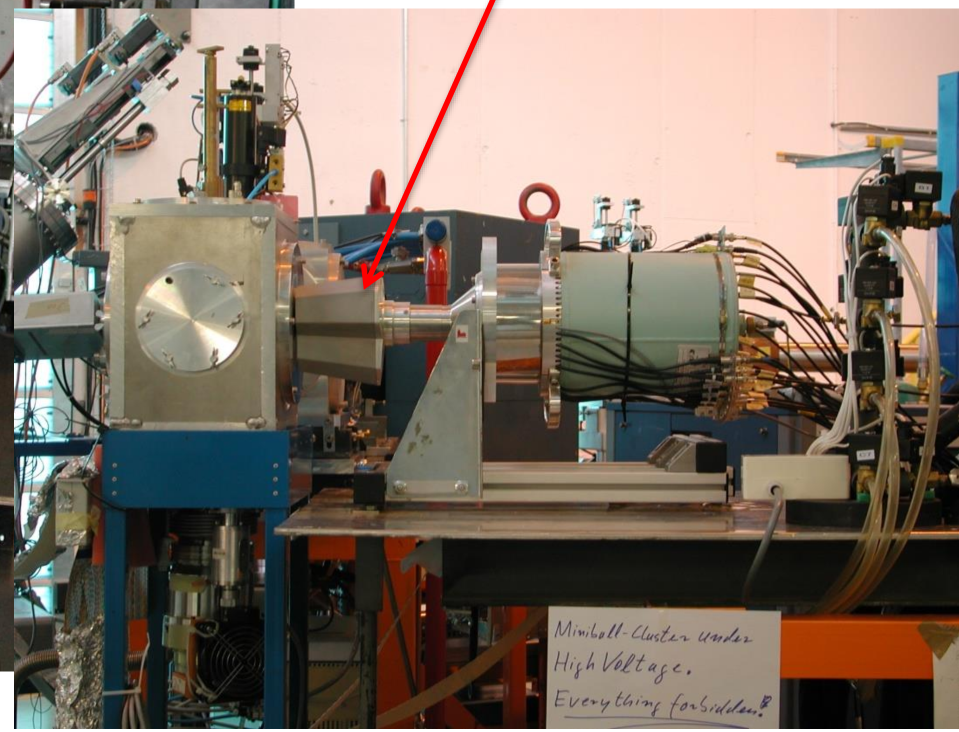
From in-beam data:
(line width after Doppler correction)

$\Delta\Theta = 3.3^0$

Commissioning of MINIBALL, Nov. 2001



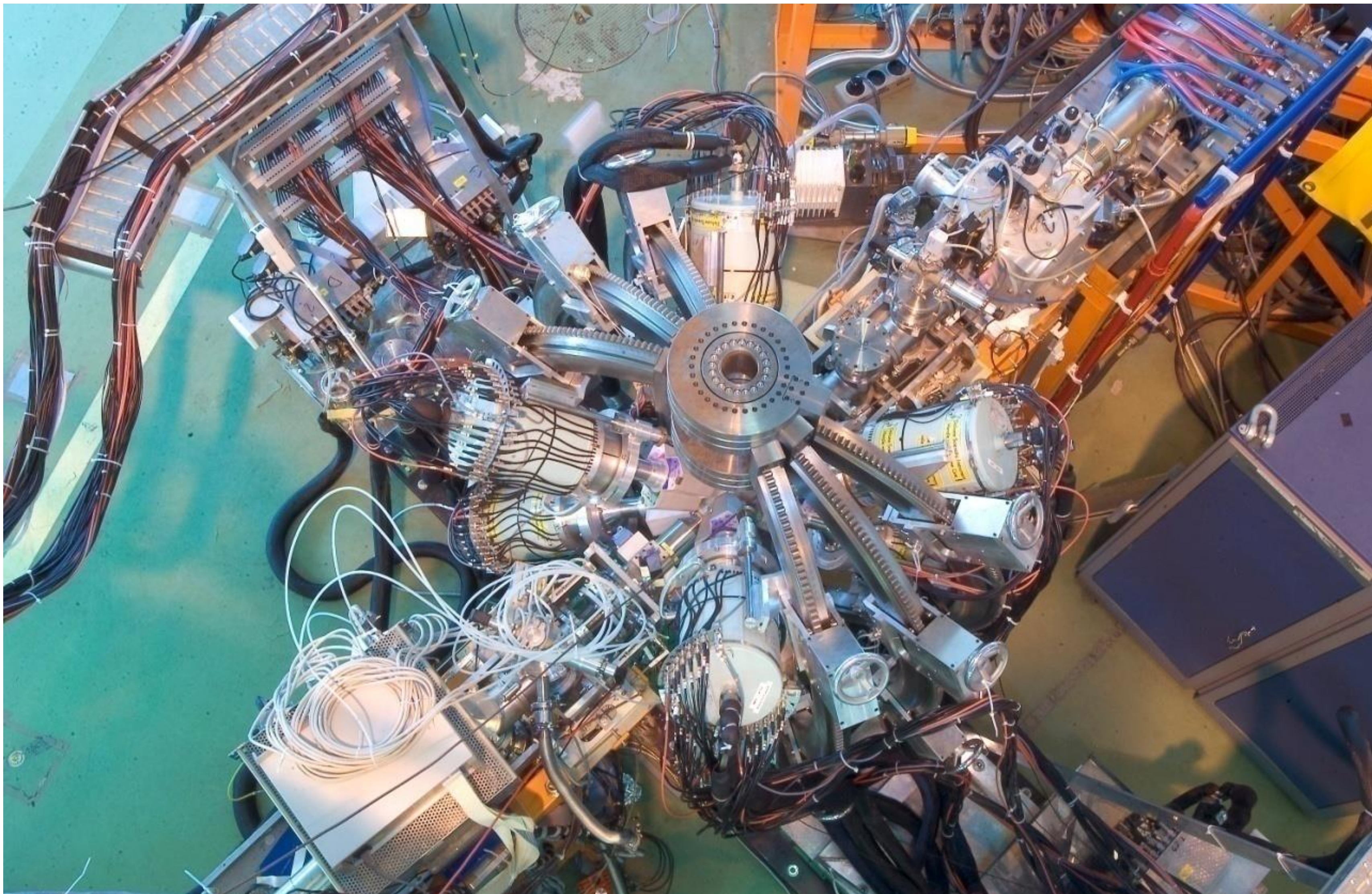
One MINIBALL Cluster Detector



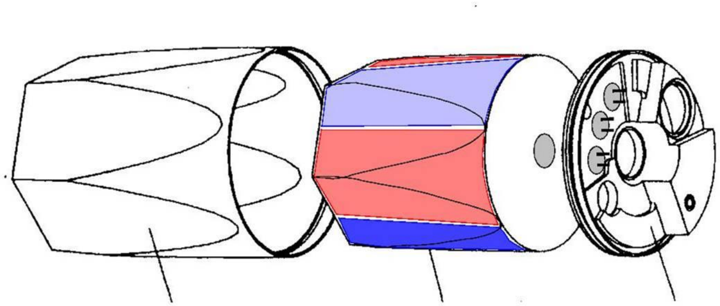
2002: 8 Triple Cluster
8 % eff.

MINIBALL at REX-ISOLDE:

Pionierung position-sensitive Ge detectors



MINIBALL

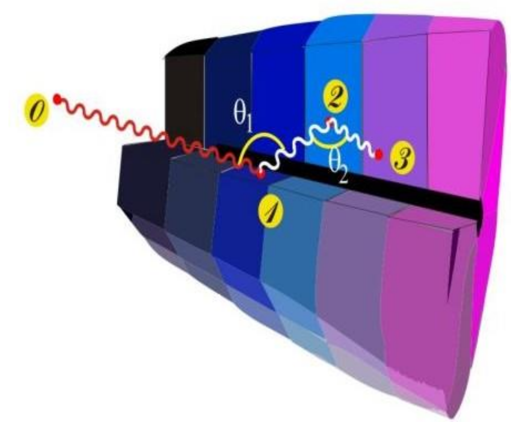


longitudinal-segmented detector
digital electronics
pulse shape analysis
detect first interaction point
24 detectors, $\Delta\theta \sim 3.3^0$

Milestone 4

AGATA

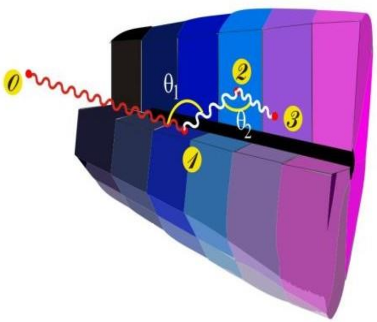
highly-segmented detector (36-fold)
digital electronics
pulse shape analysis
γ-ray tracking
180 detectors, $\Delta\theta \sim 1^0$



Ingredients of Gamma-Ray Tracking

1

Highly segmented HPGe detectors



2

Digital electronics to record and process segment signals

3

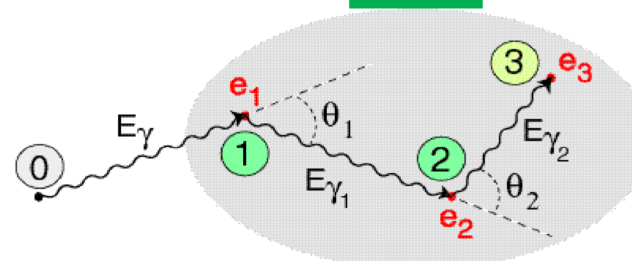
Pulse Shape Analysis to decompose recorded waves

Identified interaction points

$(x,y,z,E,t)_i$

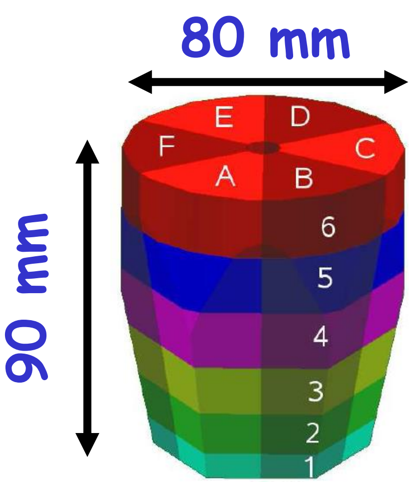
4

Reconstruction of tracks evaluating permutations of interaction points

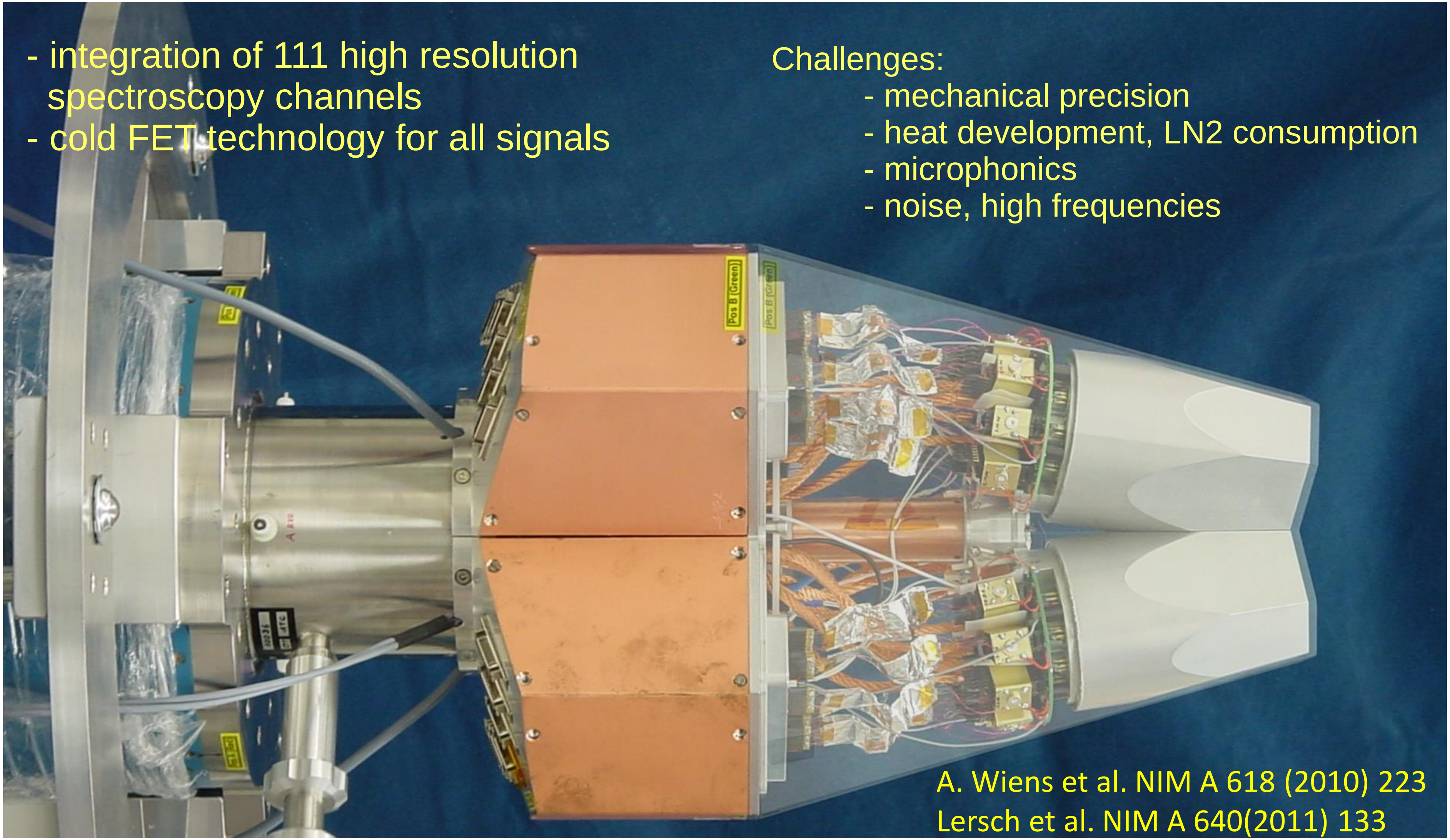


Reconstructed gamma-rays

AGATA Components

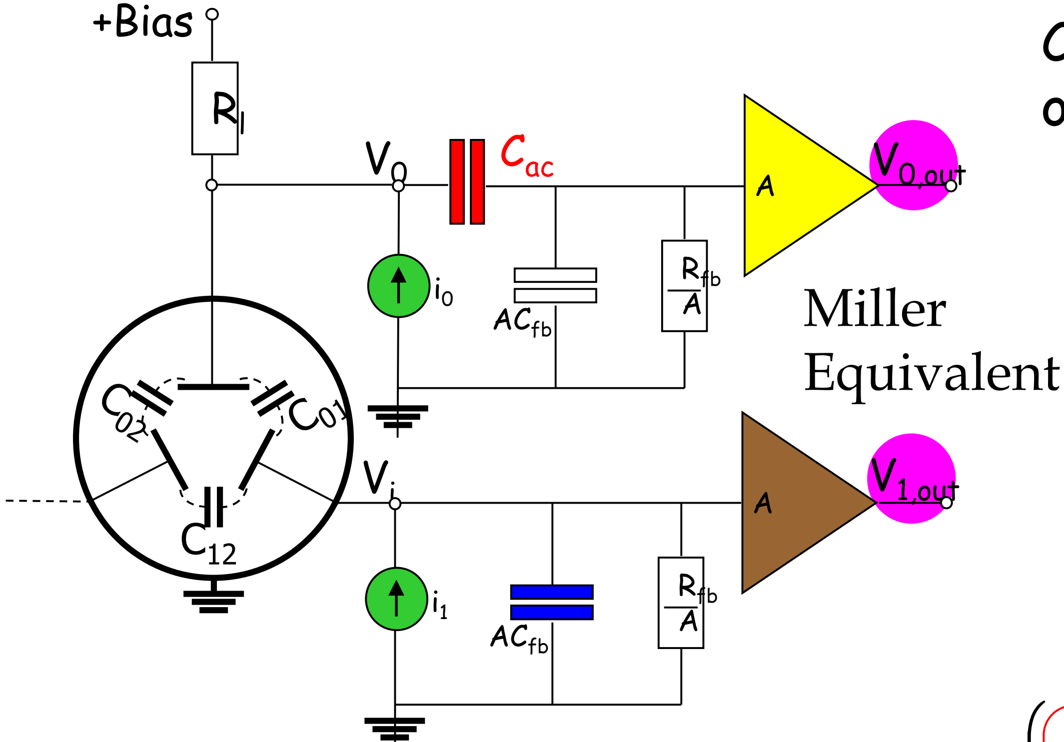


Asymmetric AGATA Triple Cryostat



Energy resolution:	2.1 keV for segments and	2.3 keV for core	at 1.3 MeV
	1.0 keV	1.3 keV	at 60 keV

A model to describe cross talk



Cross talk is intrinsic property of segmented detectors !

Segment-to-Core

$$\vec{v}_{out} \cong \frac{1}{sC_{fb}} \begin{pmatrix} 1 & -C_{01}/AC_{fb} & -C_{02}/AC_{fb} \\ -C_{01}/C_{ac} & 1 & -C_{12}/AC_{fb} \\ -C_{02}/C_{ac} & -C_{12}/AC_{fb} & 1 \end{pmatrix} \vec{i}$$

Core-to-Seg

~ 1pF/1000pF

Segment-to-Segment

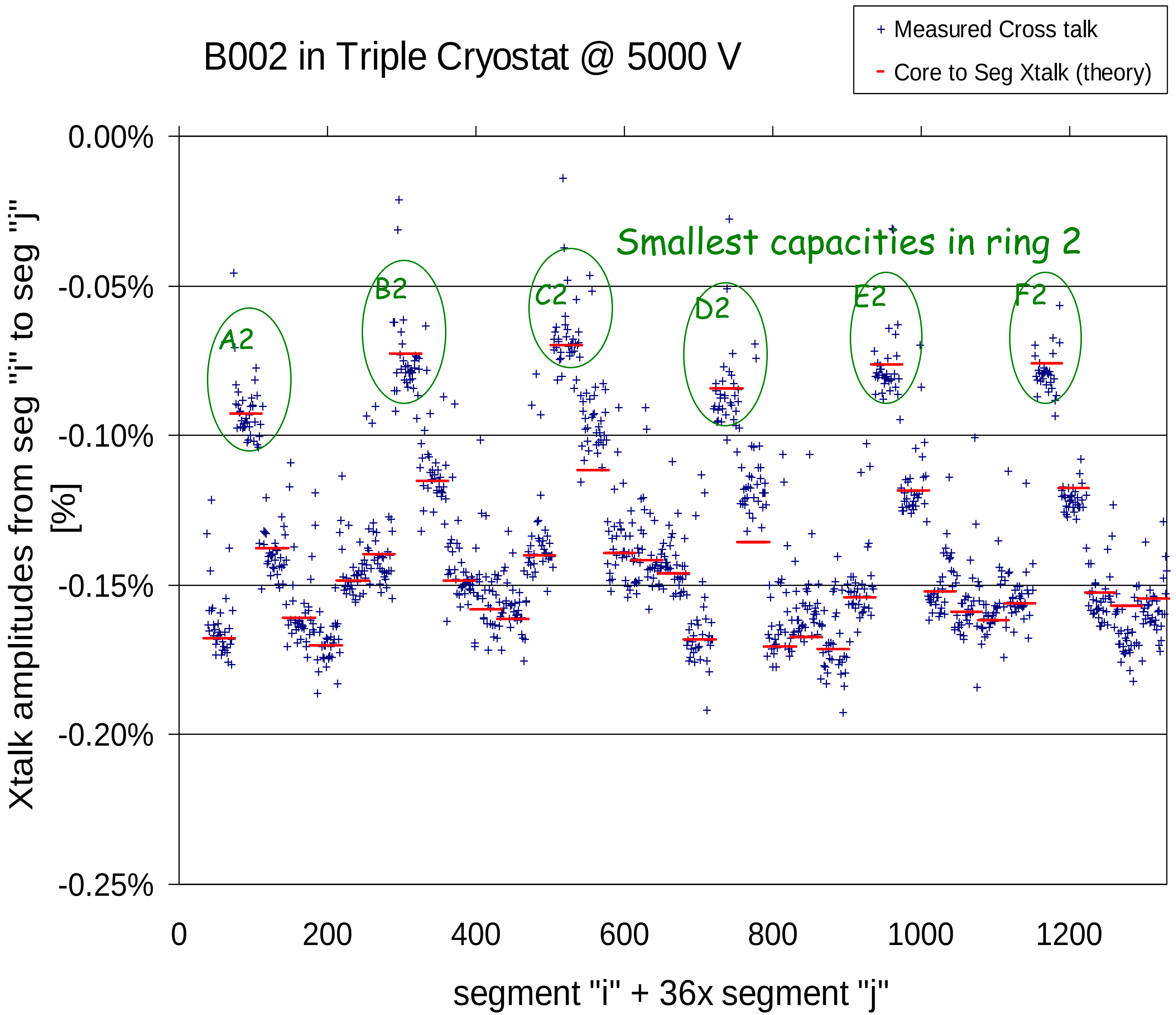
~1pF/(10000 · 1pF)

Proportional cross talk - Energy

Derivative cross talk – PSA

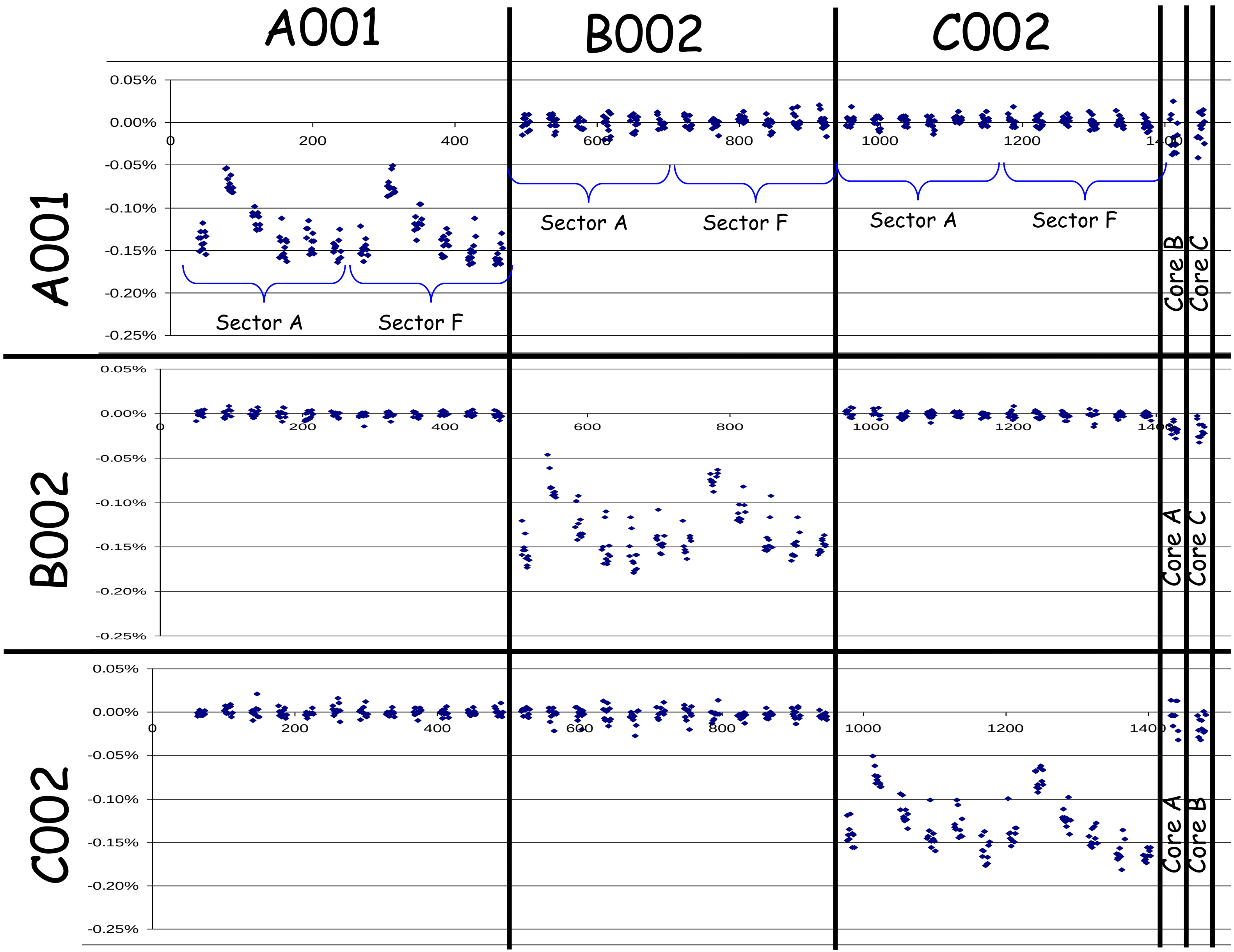
Talk by B. Bruyneel

B. Bruyneel et al., NIM A 599 (2009) 196

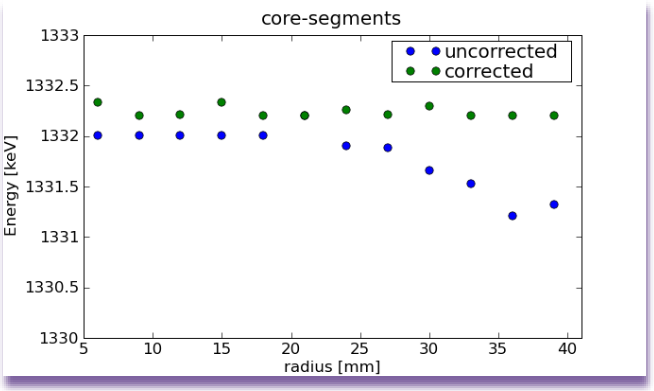


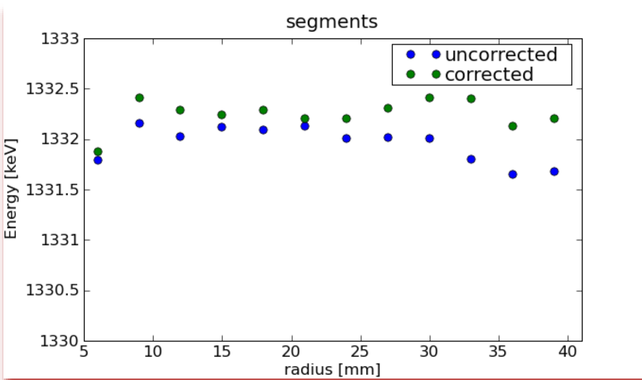
B002 in Triple Cryostat @ 5000 V
Measured Cross talk
Core to Seg Xtalk (theory)
Smallest capacities in ring 2
A2
B2
C2
D2
E2
F2
0.00%
-0.05%
-0.10%
-0.15%
-0.20%
-0.25%
Xtalk amplitudes from seg "i" to seg "j" [%]
0
200
400
600
800
1000
1200
segment "i" + 36x segment "j"

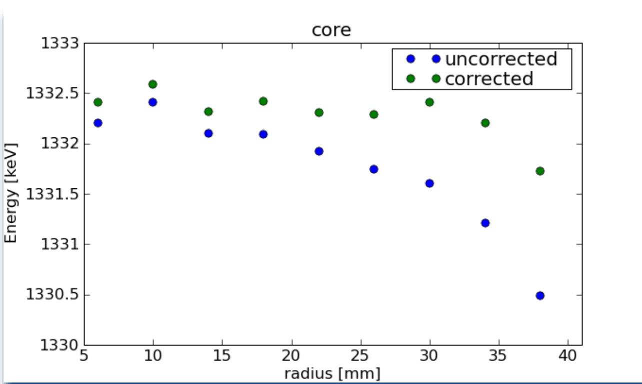
Cross talk in AGATA Triple Cluster



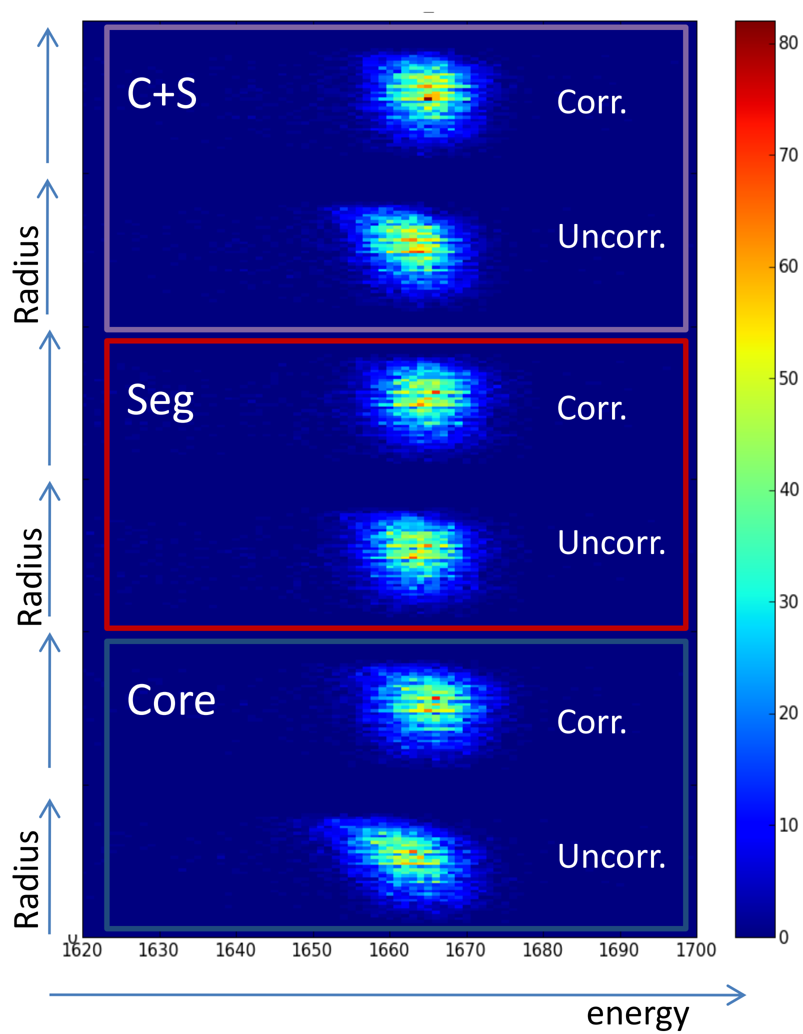
Coaxial part of detector







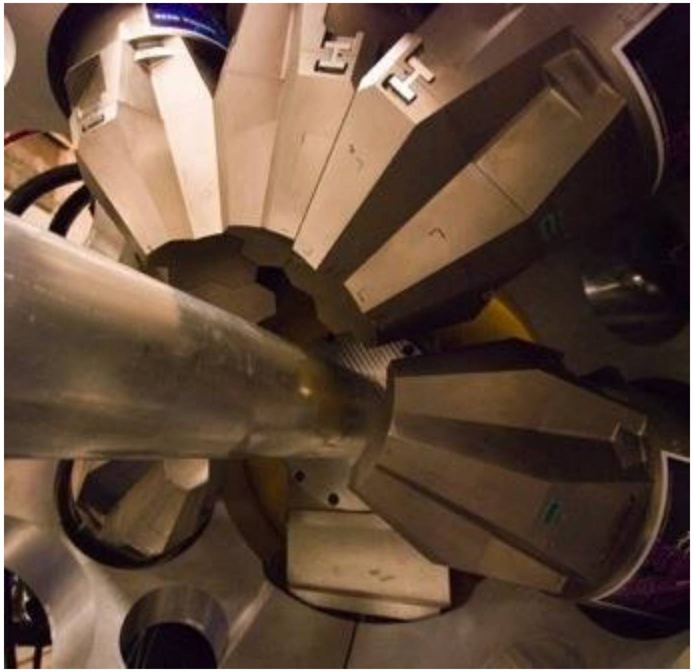
- Electron trapping present in any detector
- Source of scattering on Fano factors



FWHM 1.3MeV	FWTM / FWHM
1.80	1.85
1.87	1.85
1.93	1.86
1.98	1.83
2.12	1.81
2.25	1.83

The γ-ray tracking arrays AGATA and GRETINA are operational and delivering excellent physics results

AGATA at GANIL



GRETINA at NSCL

Is this the end of the development ?

R & D is never at the end, but always at the beginning !

AGATA
simulated performance

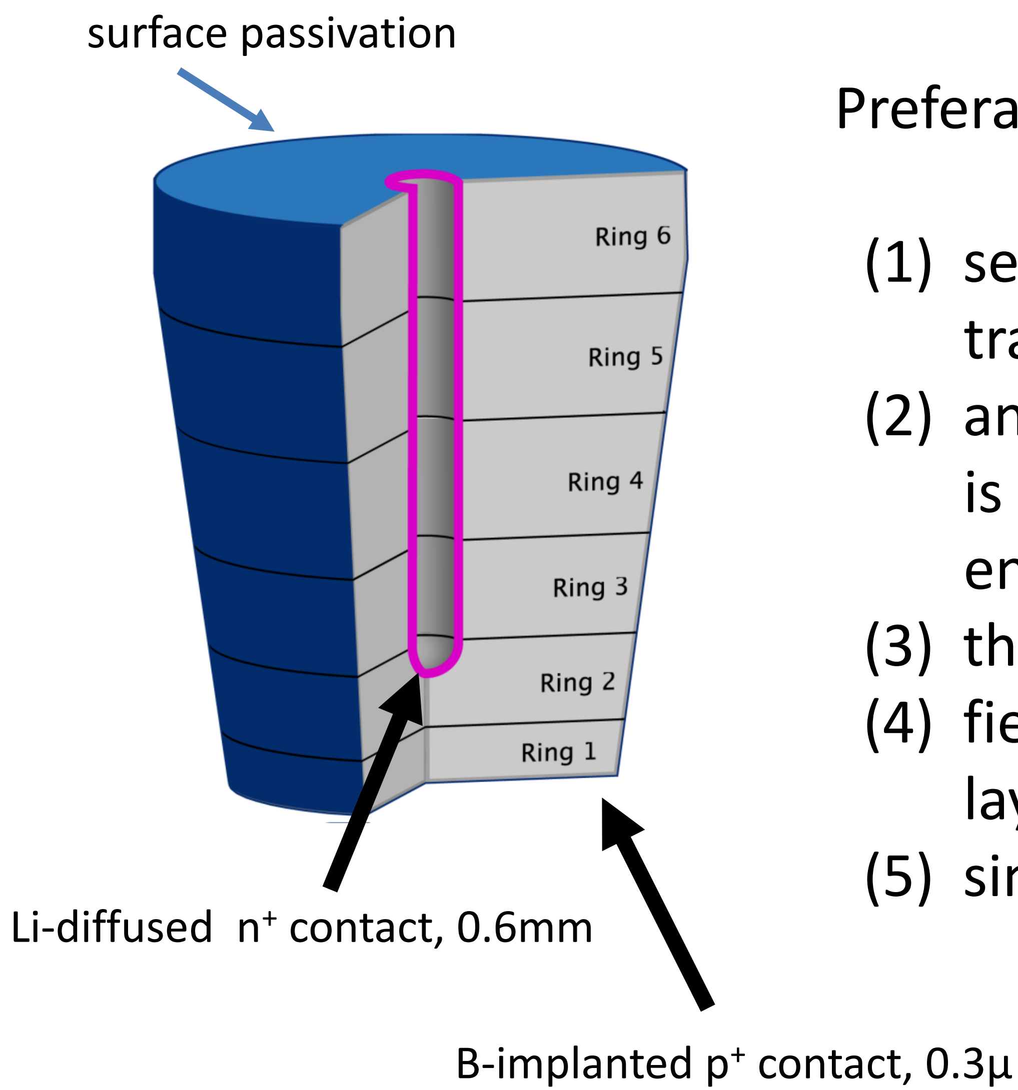
Efficiency: 43% (M_γ=1) 28% (Mγ=30)
(M_γ=30)
Peak/Total: 58% (M_γ=1) 49% (M_γ=30)
$\Delta\Theta \sim 1^0$

So far, we cannot reproduce the simulated efficiency and P/T

Pulse shape analysis and tracking algorithms to be improved

Ge detector technology to be improved

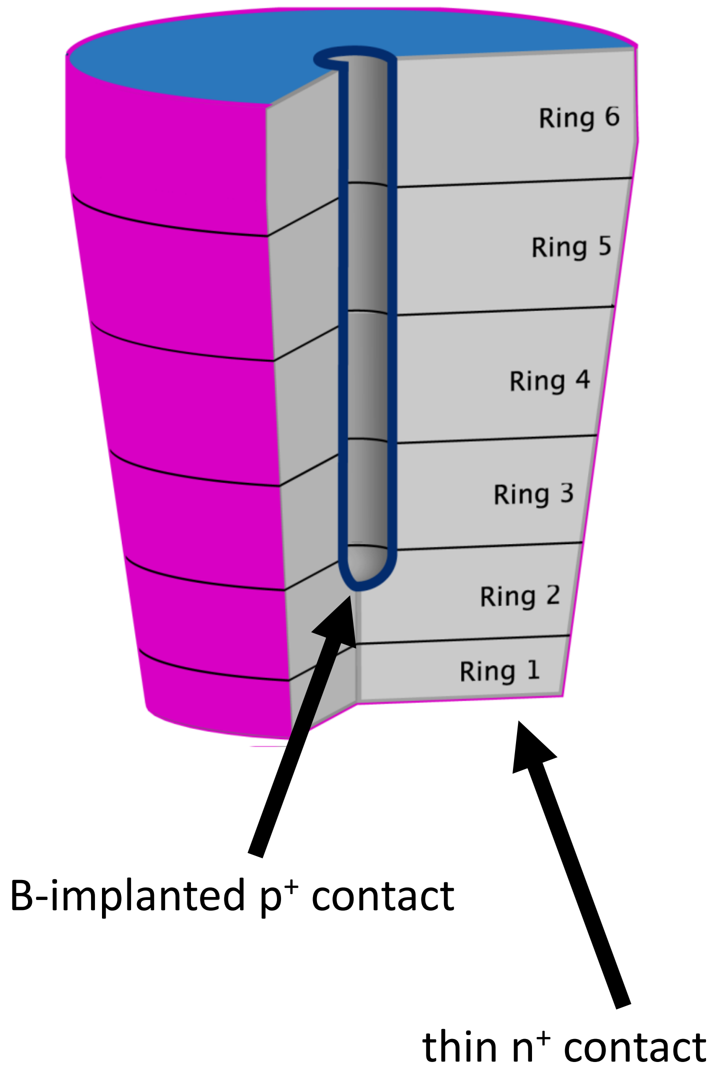
AGATA Detector, n-type Ge



Preferable Improvements:

(1) segment signals suffer from hole trapping after neutron damage
(2) annealing temperature of 102 ^{0}C is too low to fully recover the energy resolution
(3) thick n$^+$ contact with gradient
(4) field distortion below passivation layer
(5) simpler and faster encapsulation

AGATA Detector, p-type Ge



(1) segment signals suffer from hole trapping after neutron damage

Solution:
Use p-type Ge with thin and segmented n^+ contact
(amorphous Ge or ?)

AGATA Detetor n-type or p-type

(2) Annealing temperature of 102 ^{0}C is too low to fully recover the energy resolution

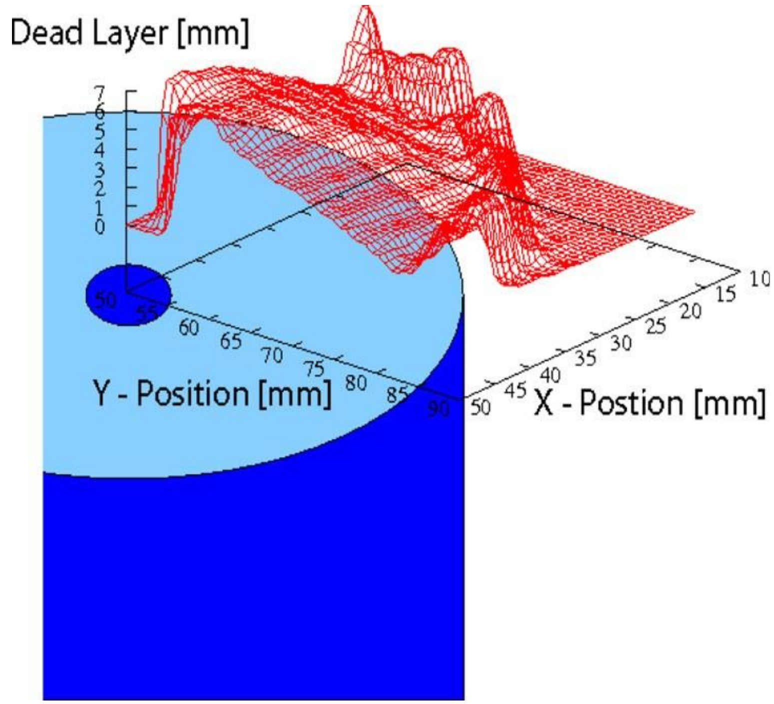
Solution:
Modify the internal parts of the encapsulated Ge detector to withstand 150 ^{0}C

(3) Thick n^+ contact with a gradient

Solution:
Replace Li-diffused contact by thin n^+ contact (amorphous Ge or ?),

AGATA Detector n-type or p-type

(4) Field distortion below passivation layer



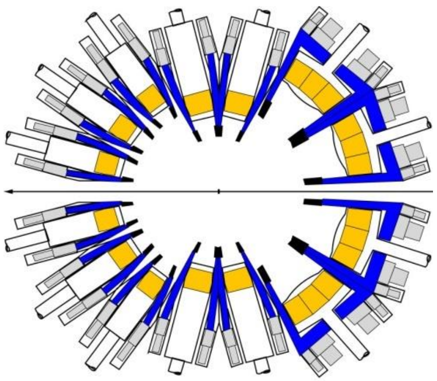
Task:

Develop a chemical passivation method which avoids surface charges and surface channels

The development of germanium detectors and technology is the result of many experts working in the field for over 50 years. Their contribution to nuclear structure physics is gratefully acknowledged.

The next generation of spectrometers

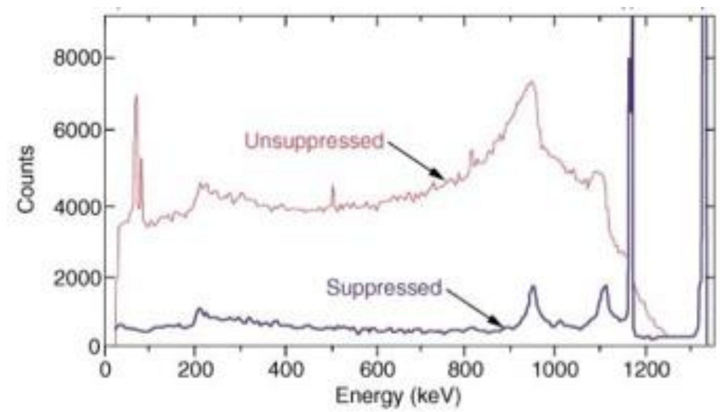
Today's spectrometers



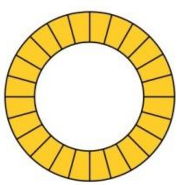
EUROBALL
N = 239

large opening angle means poor energy resolution at high recoil velocity

too many detectors are needed to avoid summing effects

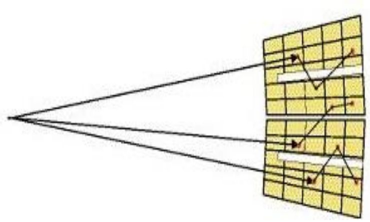


Tomorrows spectrometers



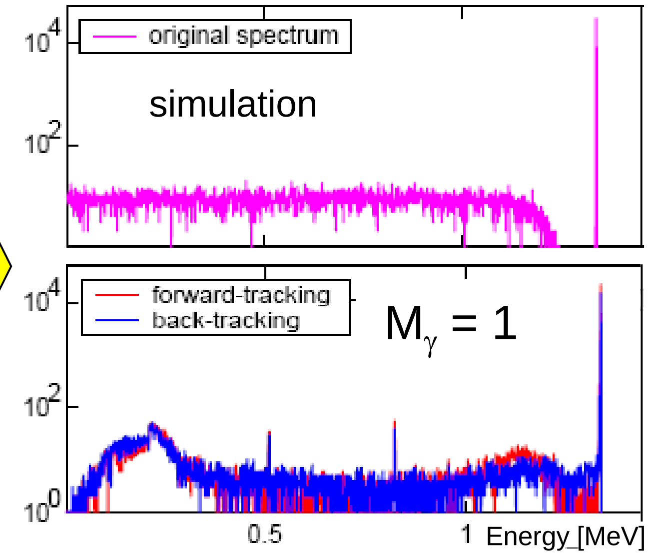
AGATA

N = 180
segmented



Combination of:

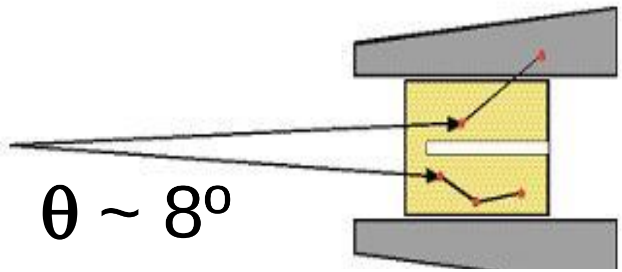
- segmented detectors
- digital electronics
- pulse shape analysis
- tracking the γ-rays



A. Lopez-Martens NIMA 533 (2004) 454–466

Compton Shielded Ge

ε_{ph} ~ 10%
N_{det} ~ 100
Ω ~40%



$\theta \sim 8^o$

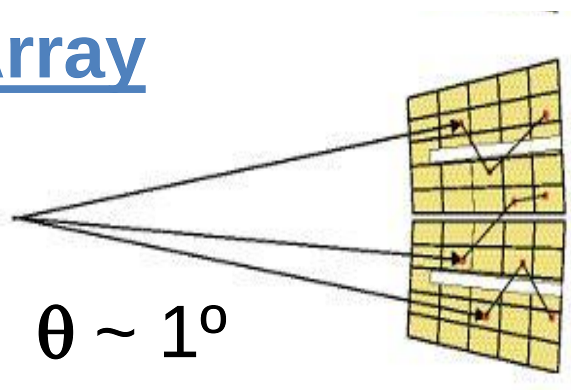
large opening angle means poor energy resolution at high recoil velocity.

Milestone 4

Previously we had to waste scattered gam .
Technology is available now to track the

Ge Tracking Array

ε_{ph} ~ 40%
N_{det} ~ 150
Ω ~80%



$\theta \sim 1^o$

Combination of:

- segmented detectors
- digital electronics
- pulse processing
- tracking the γ-rays