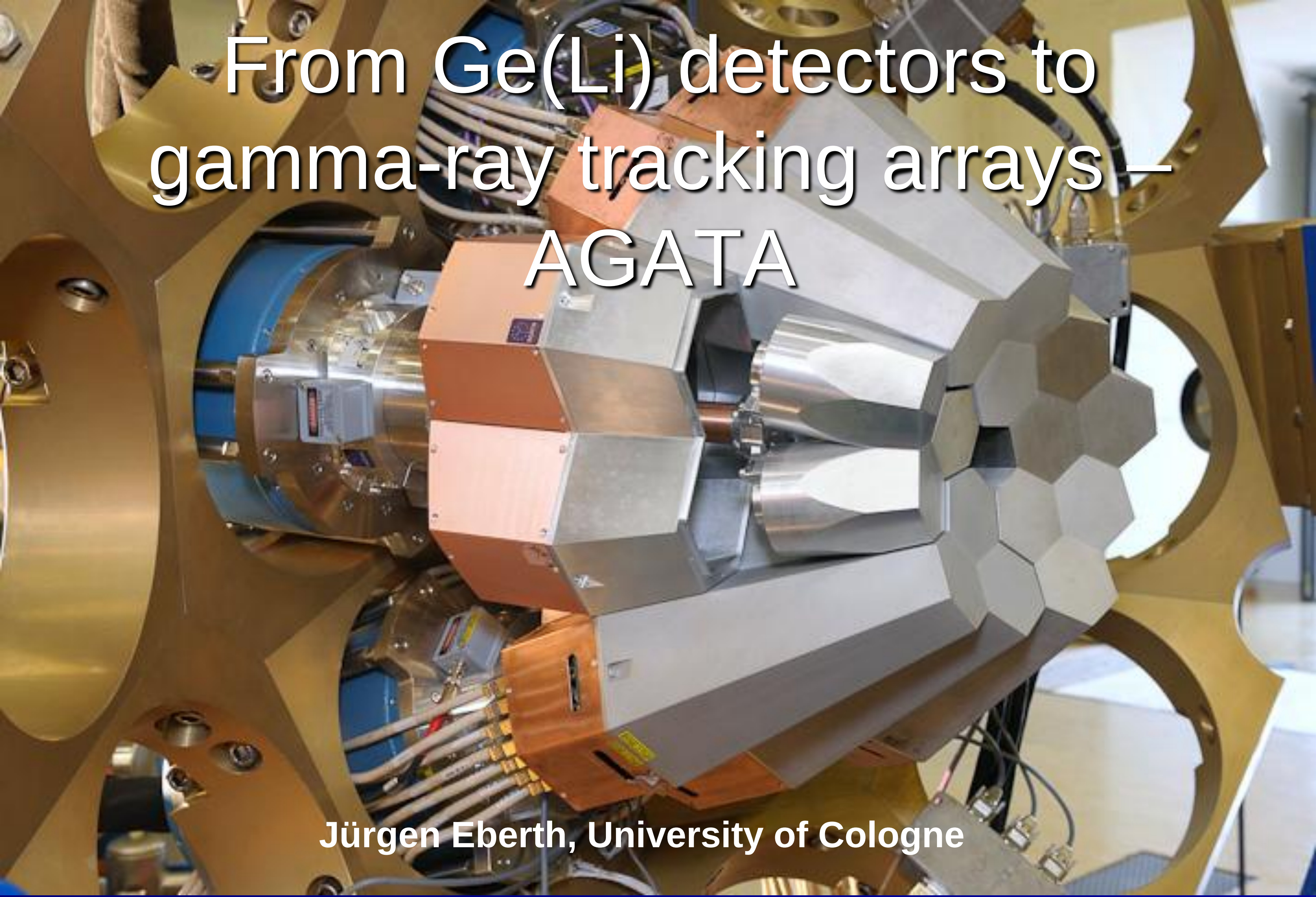


From Ge(Li) detectors to gamma-ray tracking arrays – AGATA

Jürgen Eberth, University of Cologne

Topics to be discussed

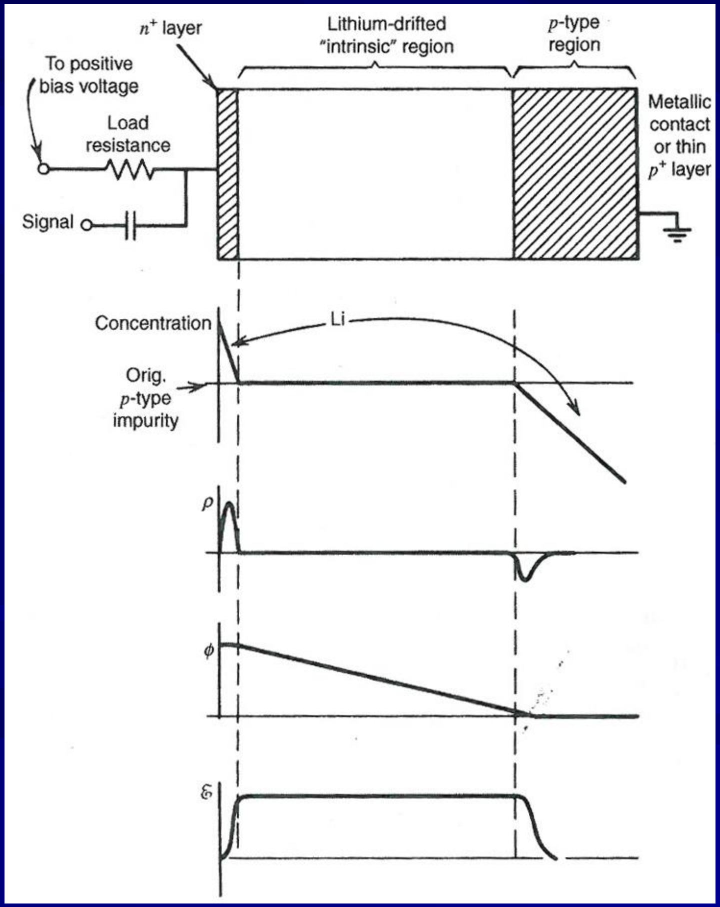
- The 1960ties and 70ties: Ge(Li) detectors
- The 1980ties: HPGe detectors arrays by national collab.
  OSIRIS, HERA, TESSA
- The 1990ties: EUROBALL and GAMMASPHERE
- The last decade: position-sensitive Ge Detectors
  MINIBALL, EXOGAM, SEGA
- Under development: the 4π gamma-ray tracking arrays
  AGATA, GRETA

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)



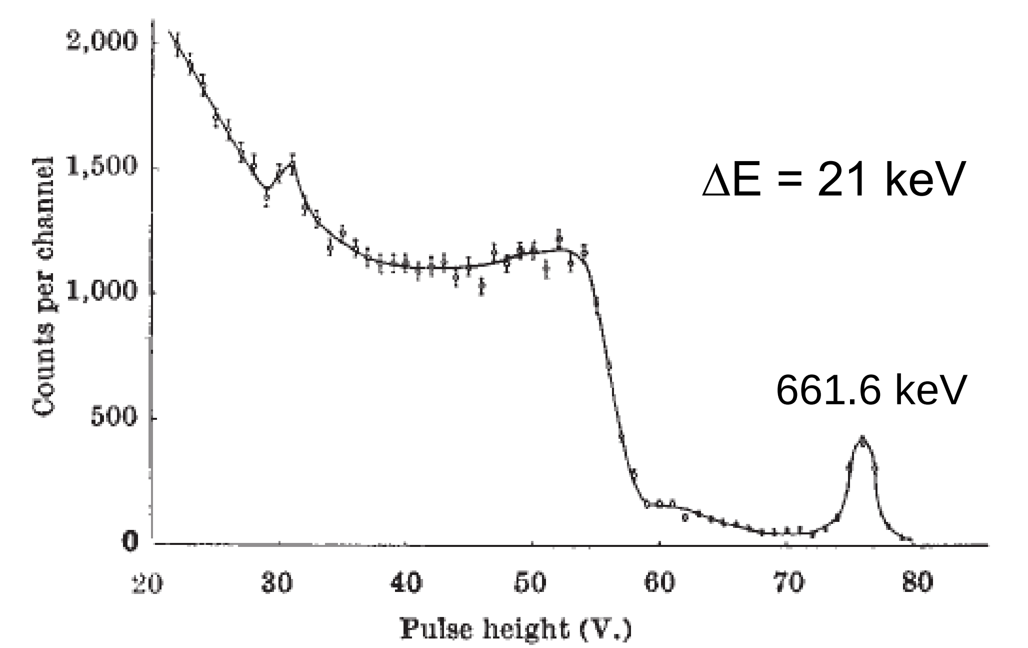
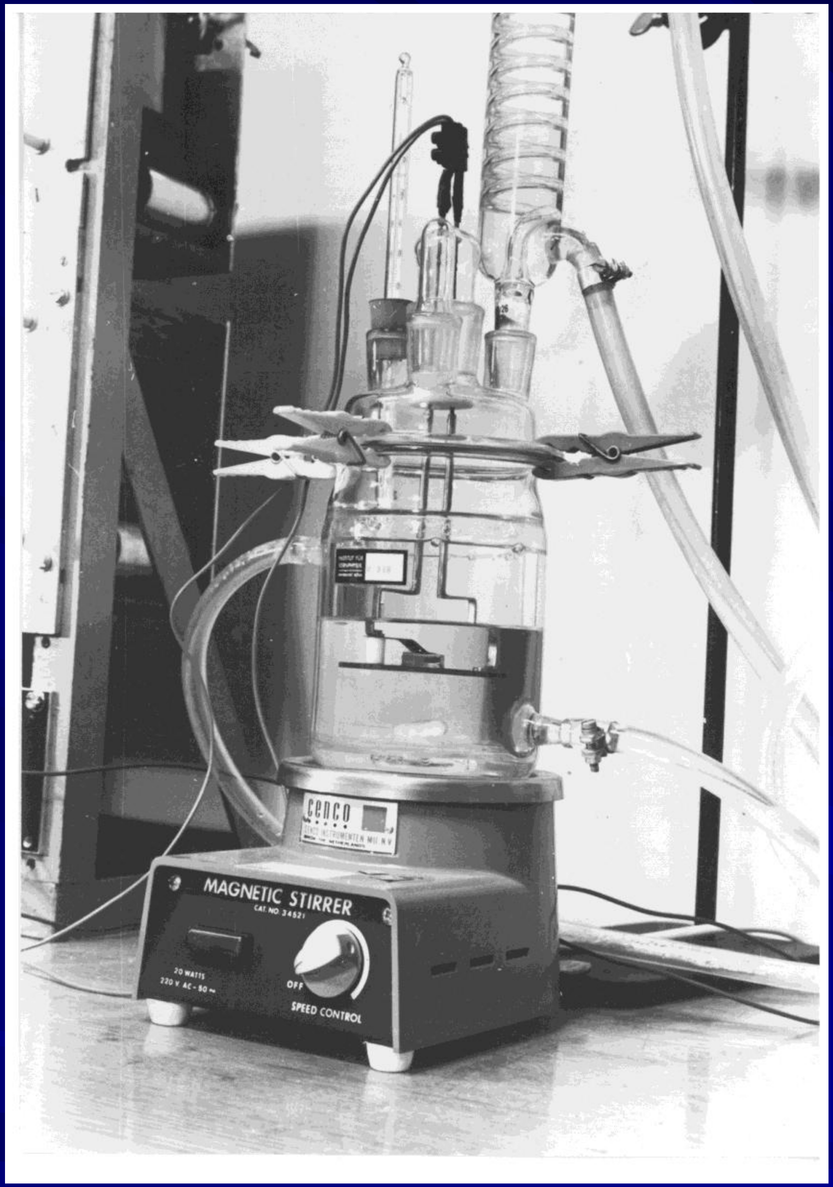
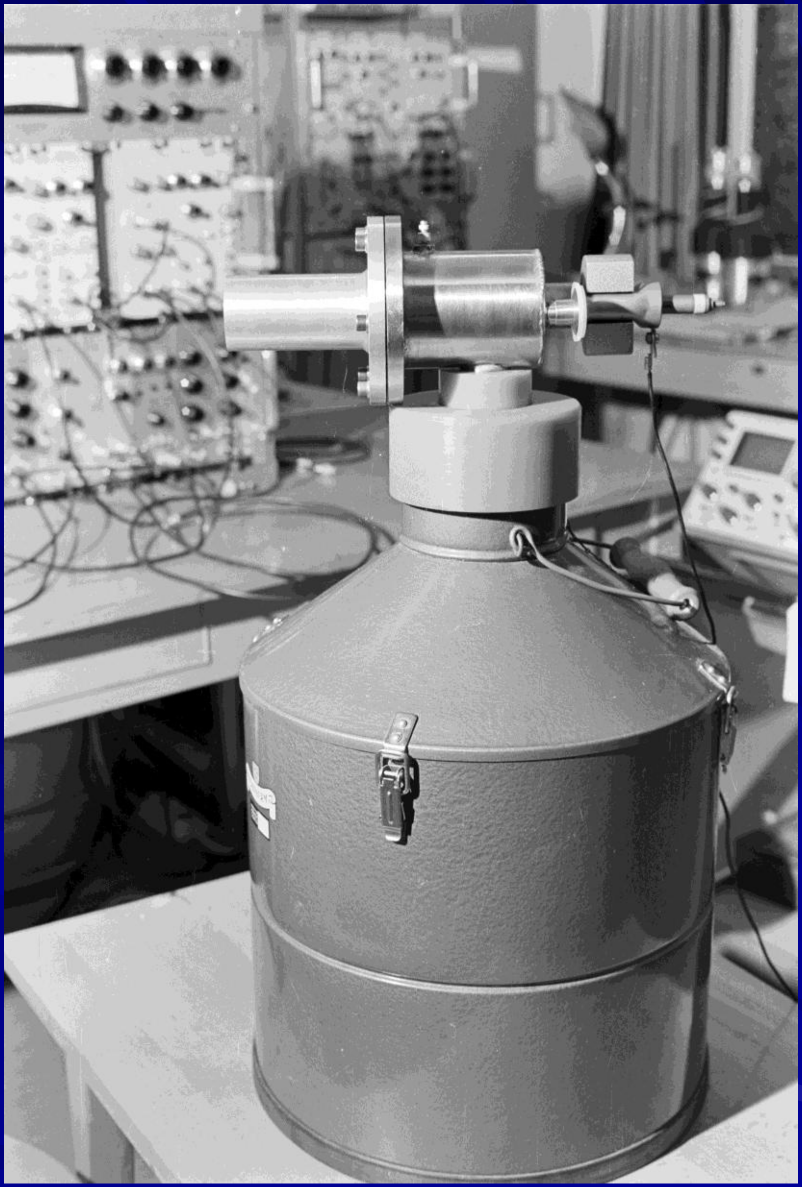


Fig. 1. Pulse-height spectrum from a *p-i-n* junction in germanium due to 663 keV. γ-rays from cæsium-137

First Ge(Li) detector: D.V.Freck and J. Wakefield
Nature 193, 669 (1962)

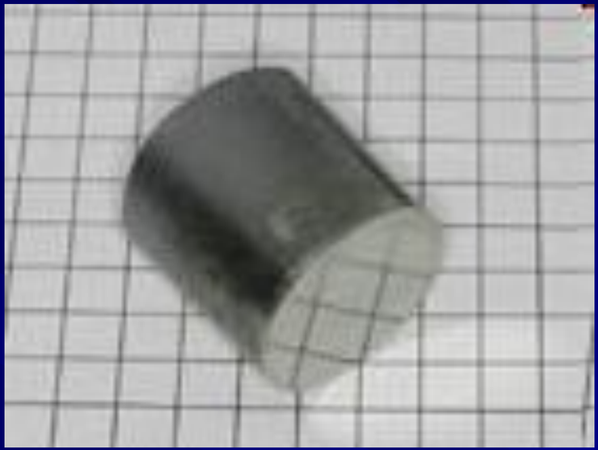


Li-drift apparatus
Univ. of Cologne 1967



Coaxial detector 1968
ΔE = 3.5 keV at 1.3 MeV

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)

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

energy resolution 3.5 – 5 keV at 1.3 MeV

Ge crystal: 65mm diam., 46mm length

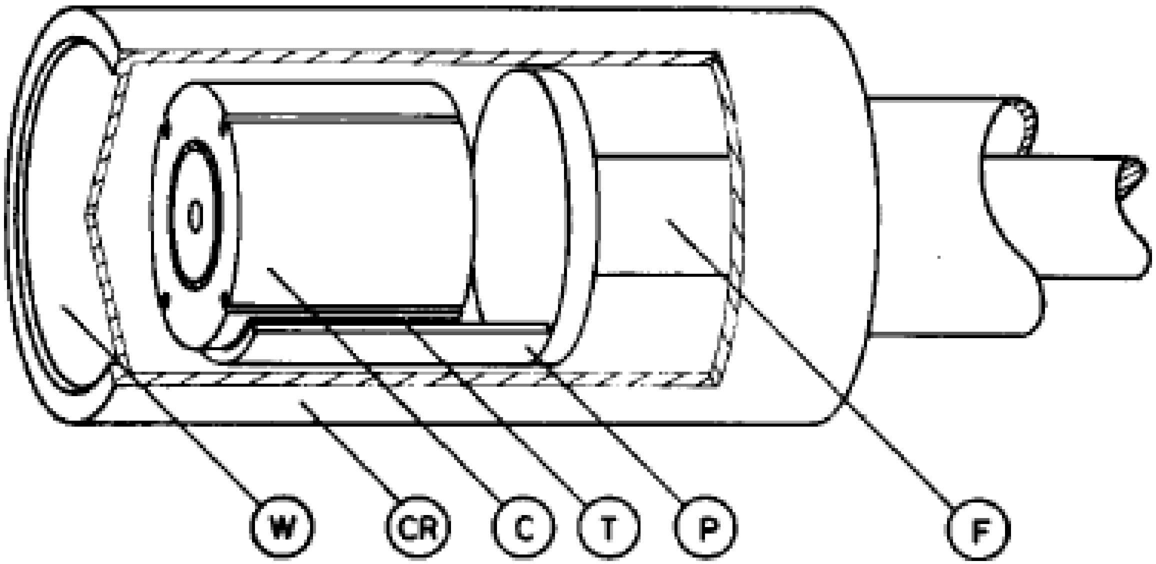


Fig. 1. Cross section of the polarimeter. W = thin window, CR = cryostat, C = crystal, T = Teflon insulation, P = crystal holder, F = cold finger.

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

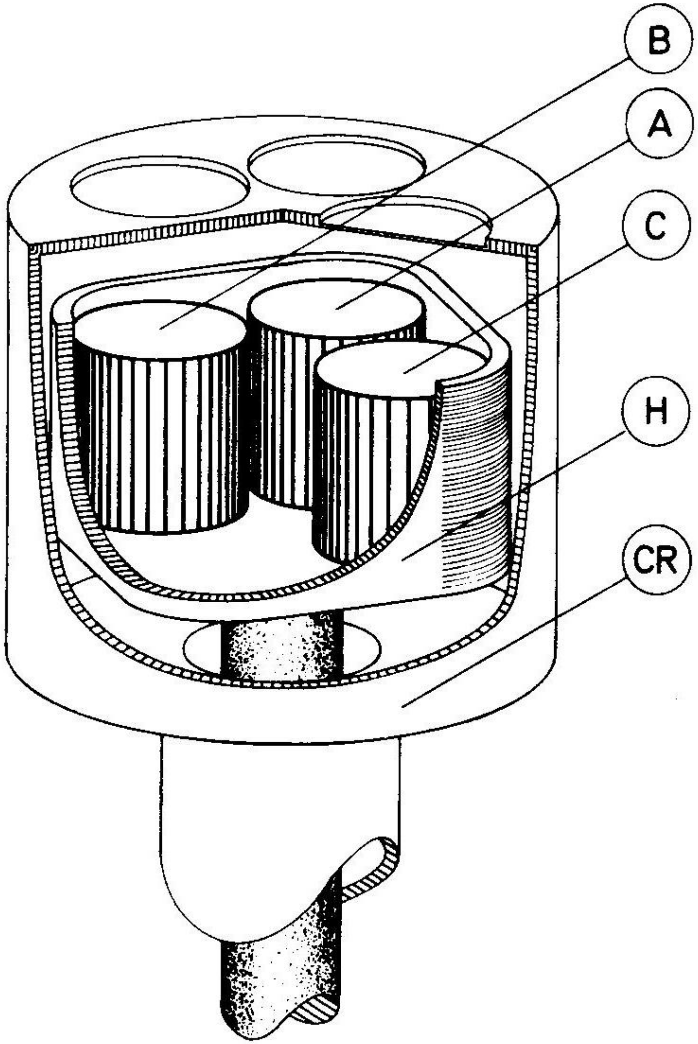


FIG. 4. Three-crystal Compton polarimeter, Detector A acts as scatterer, the absorbers B and C are shielded from direct radiation by a 4 cm collimator of Densimed (see text). CR = cryostat, H = heat shielding.

Composite Ge Detectors

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

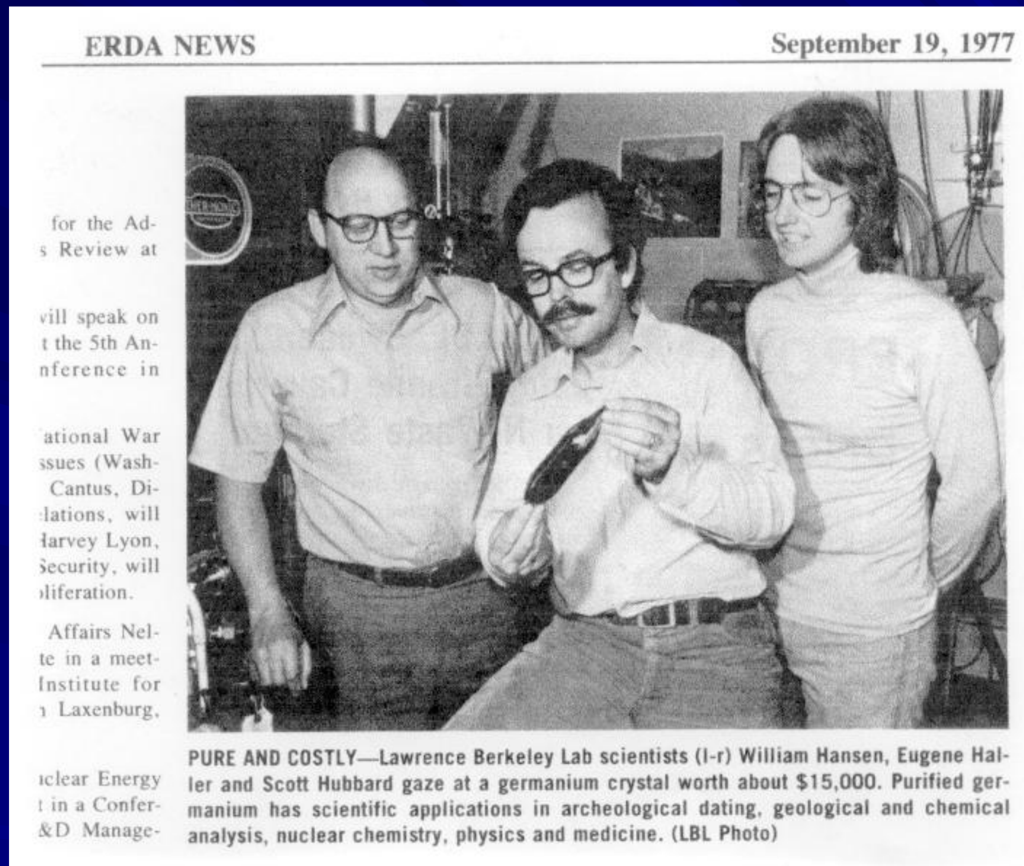
(1976)

resolution 2.1 keV at 1.3 MeV

for 3 but not for 4 detectors

Encapsulation ?

Development of high-purity Ge at LBNL, Ortec, Umicore ..



ERDA NEWS — September 19, 1977

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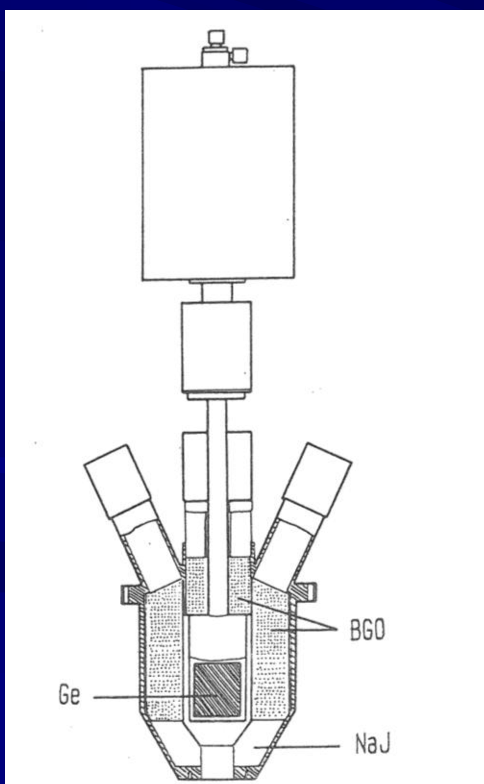
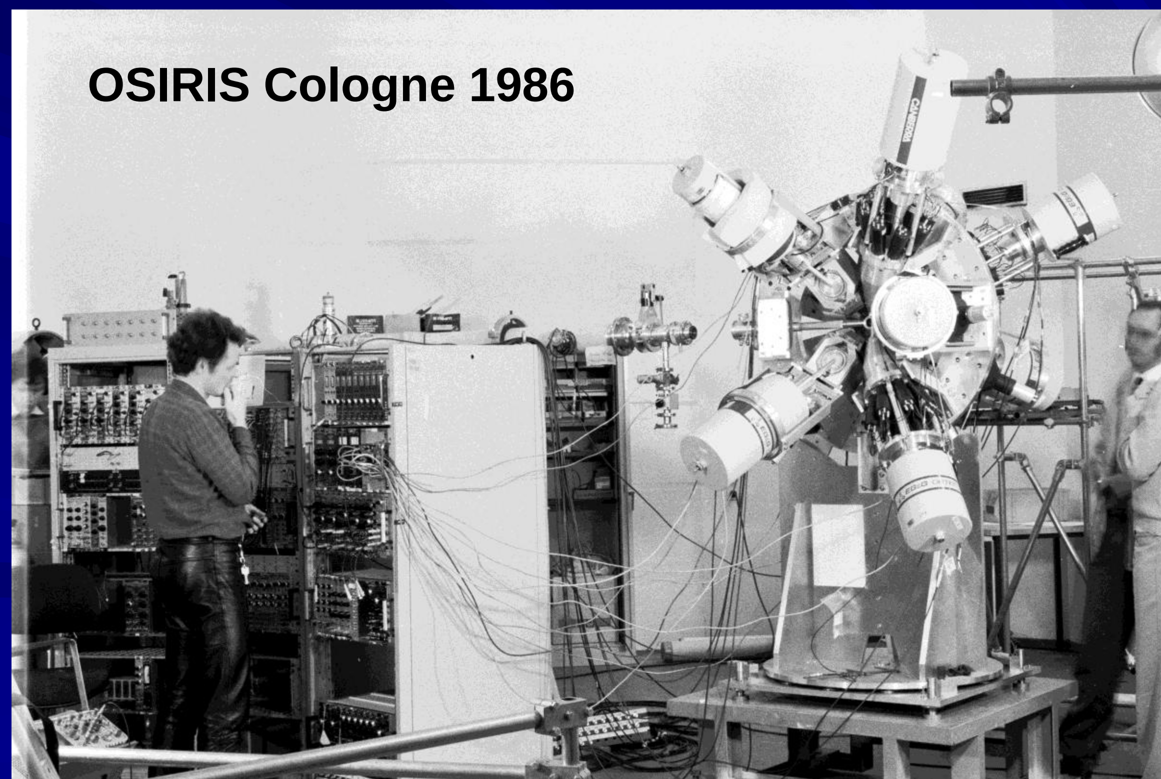
PURE AND COSTLY—Lawrence Berkeley Lab scientists (l-r) William Hansen, Eugene Haller and Scott Hubbard gaze at a germanium crystal worth about $15,000. Purified germanium has scientific applications in archeological dating, geological and chemical analysis, nuclear chemistry, physics and medicine. (LBL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

Production of Ge(Li) detectors was abandoned after 1978 when high-purity Ge (HPGe) detectors became commercially available

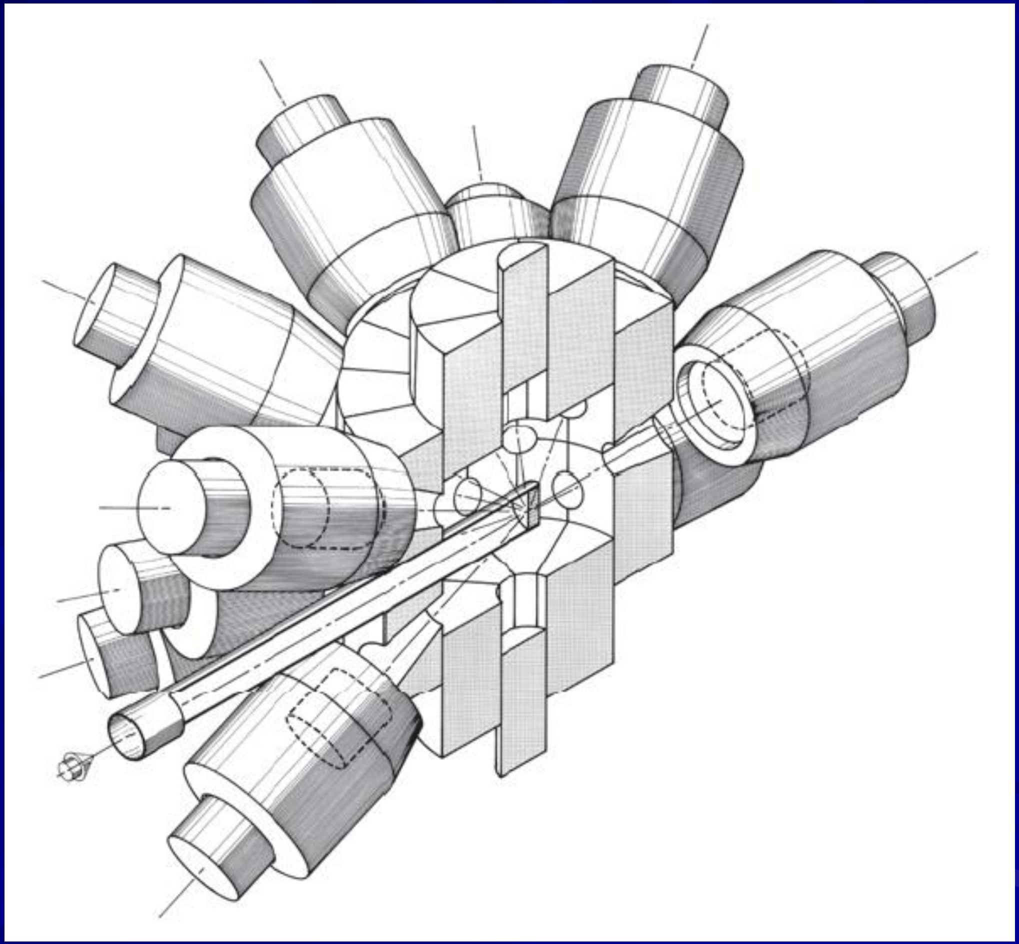
The 1980ties

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





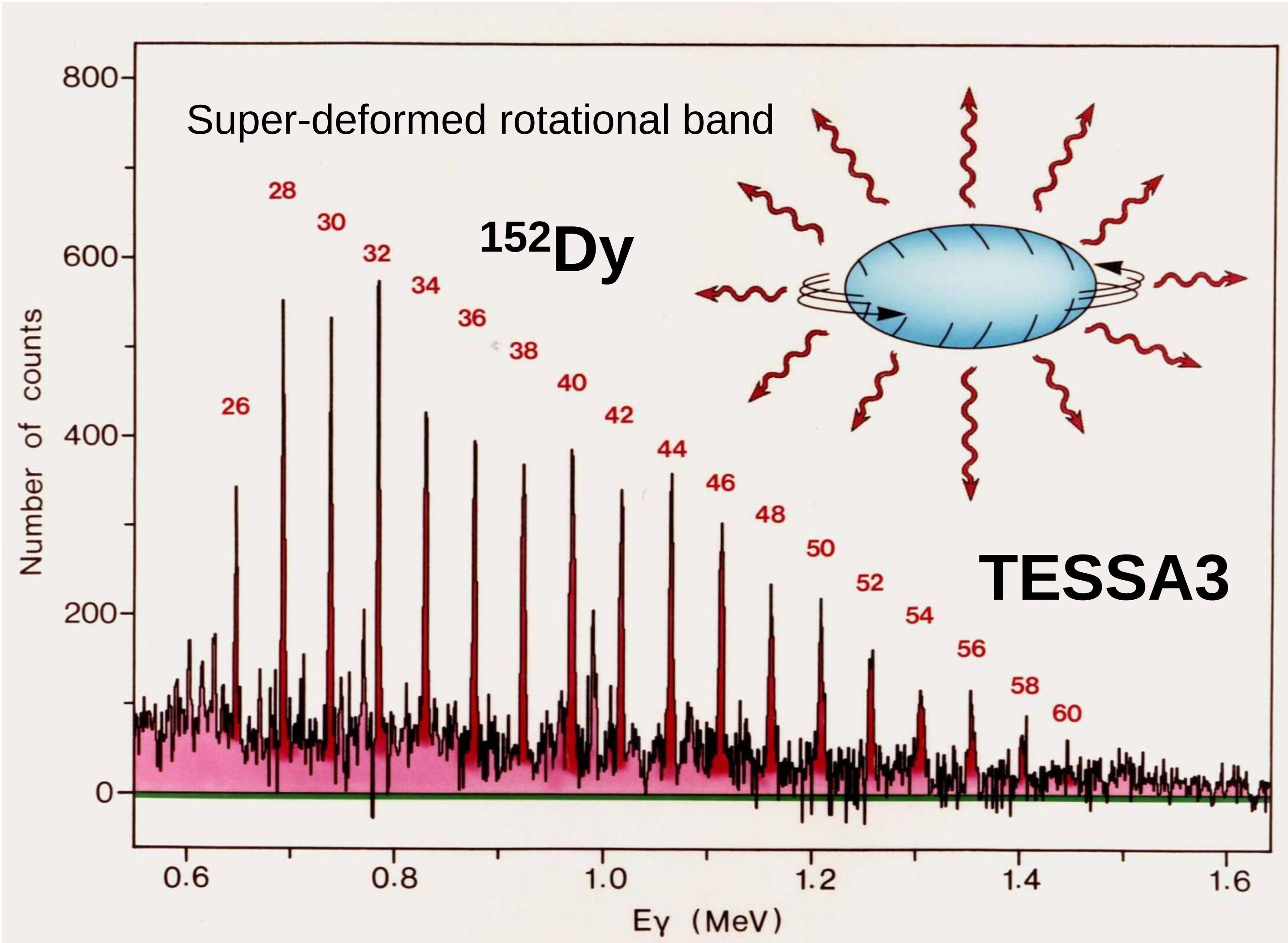
TESSA (Daresbury), NORDBALL (Risø),
8π Spectrometer (Chalk River), …



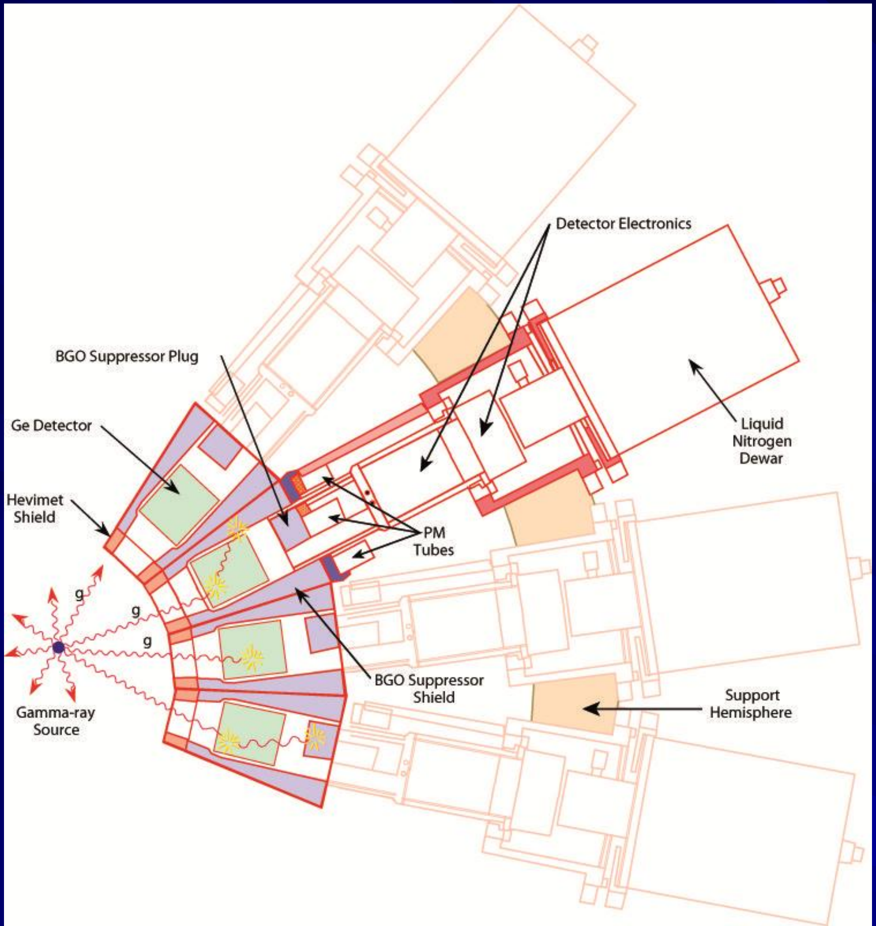
HERA
at LBNL

21 HPGe detectors (25% eff.) with escape suppr. shields

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

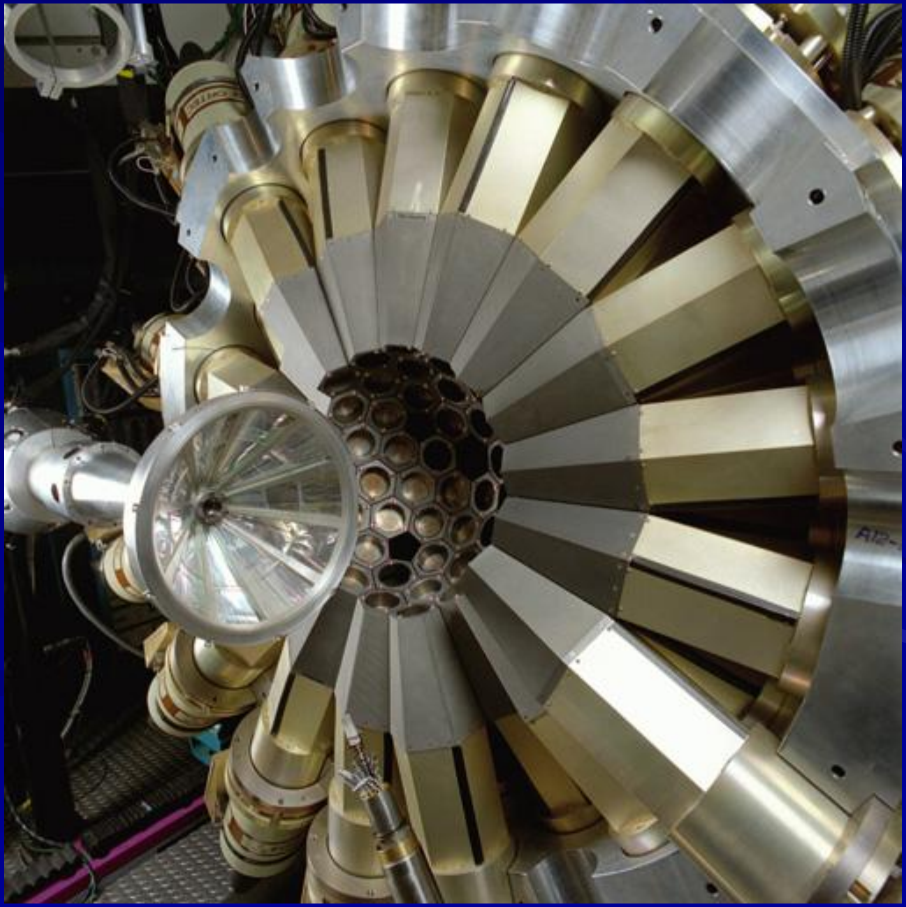


P.J. Twin et al., Phys. Rev. Lett. 57(1986)811



GAMMASPHERE
1993 Berkeley

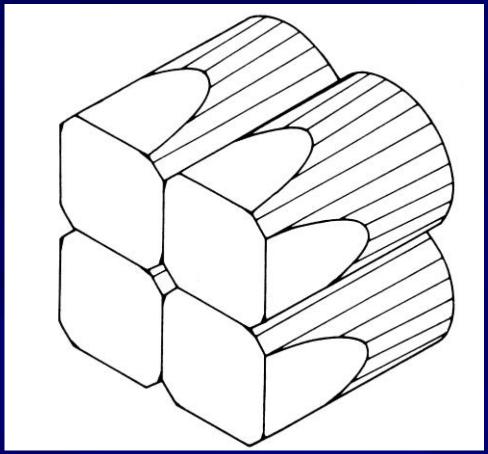
110 Ge detectors (70% eff.)
escape suppression shields



Abs. Eff. ~ 10%

70 detectors segmented into two halves to reduce the Doppler broadening

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

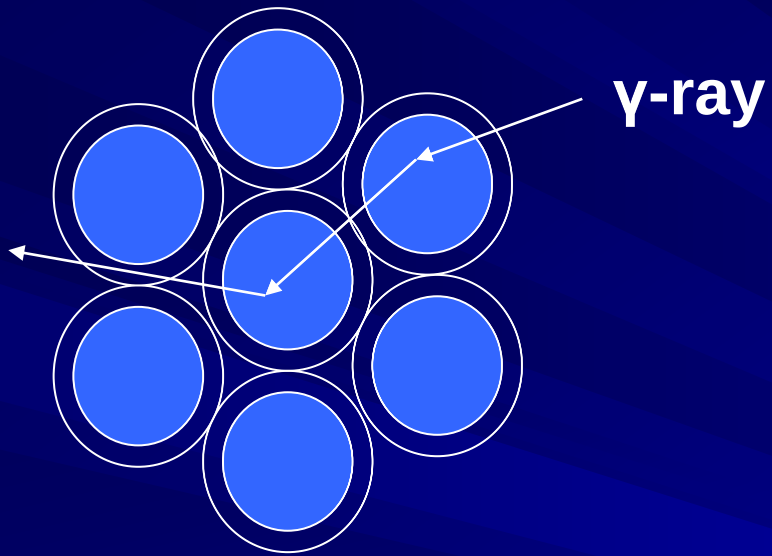


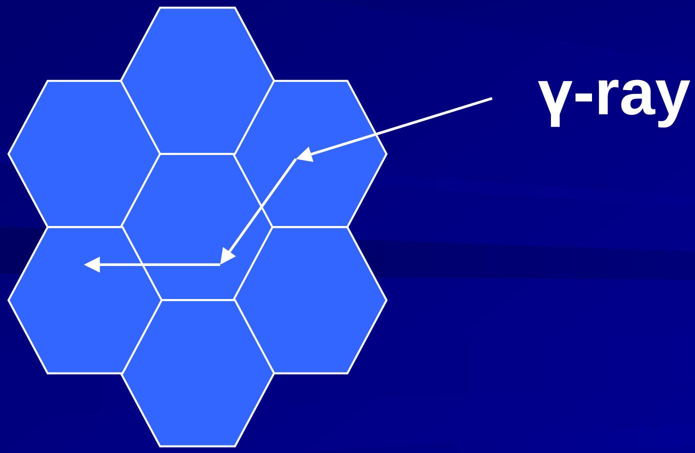
EUROGAM II

24 CLOVER detectors with increased eff. (130%)and improved granularity

F.A. Beck et al. Conf. Proc. 1994

From EUROGAM to EUROBALL





Late 1980's :

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

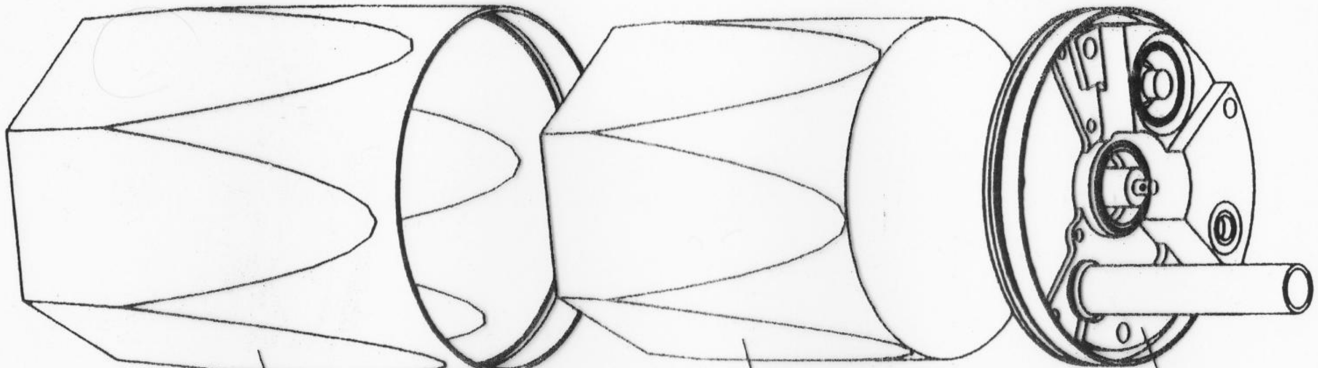
Conclusion:
seven hexagonal detectors in a common cryostat

Encapsulation !

capsule and lid sealed by electron-beam welding

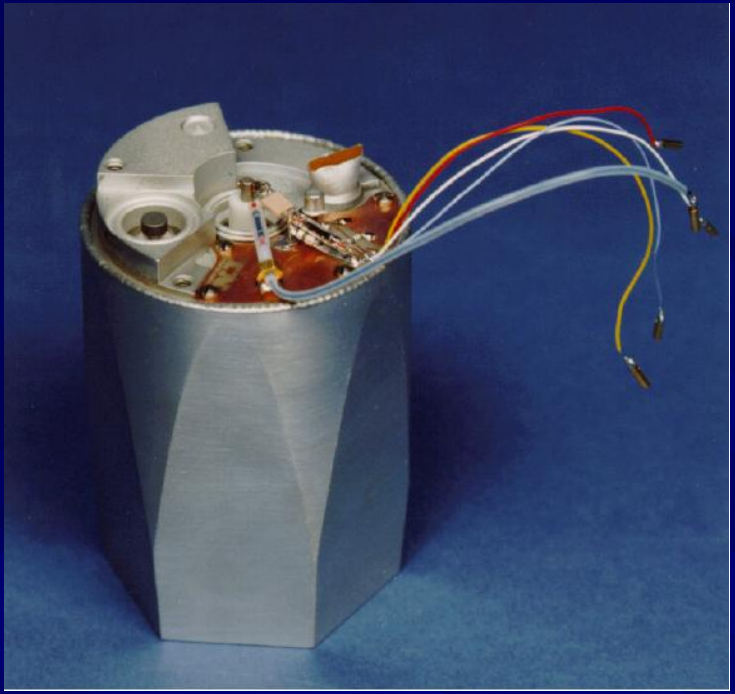
internal Getter, vacuum < 10^{-6} mb,

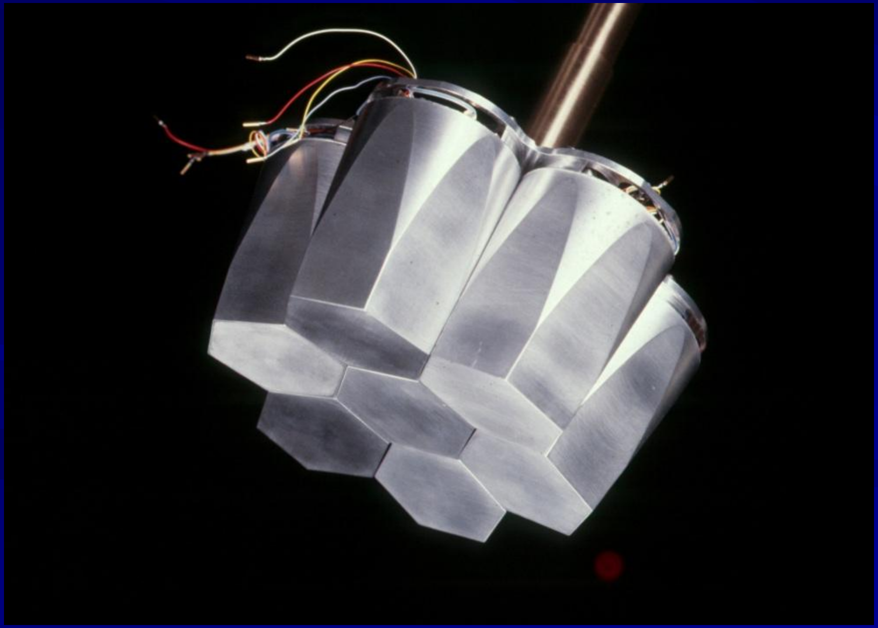
temperature range -196 ^{0}C and +110 ^{0}C

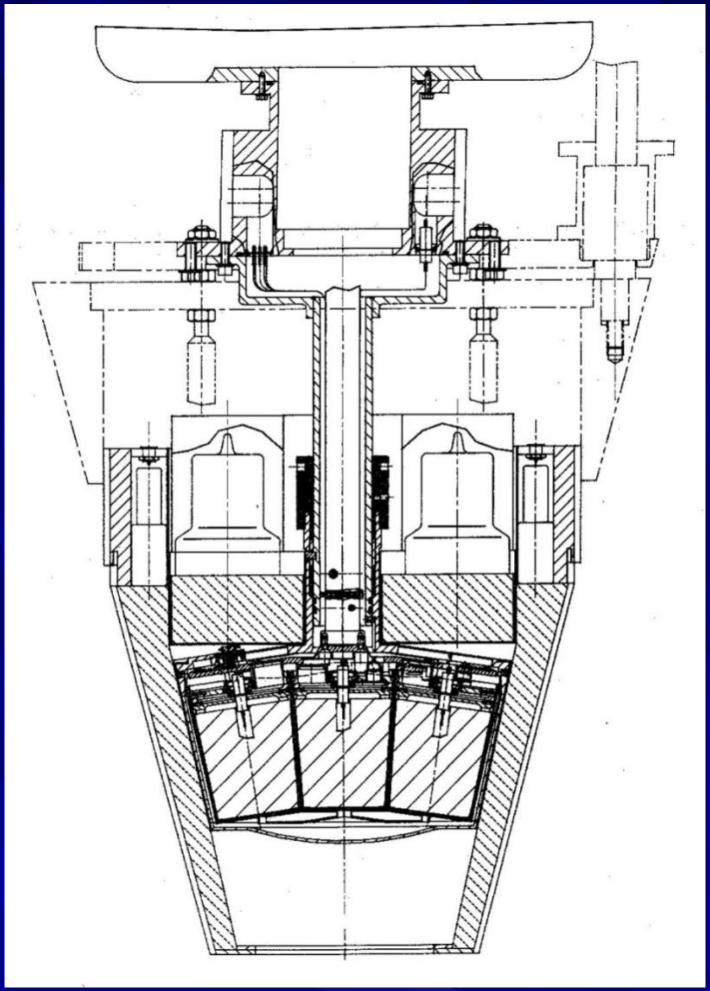


Collaboration: Köln, Jülich, Eurisys

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

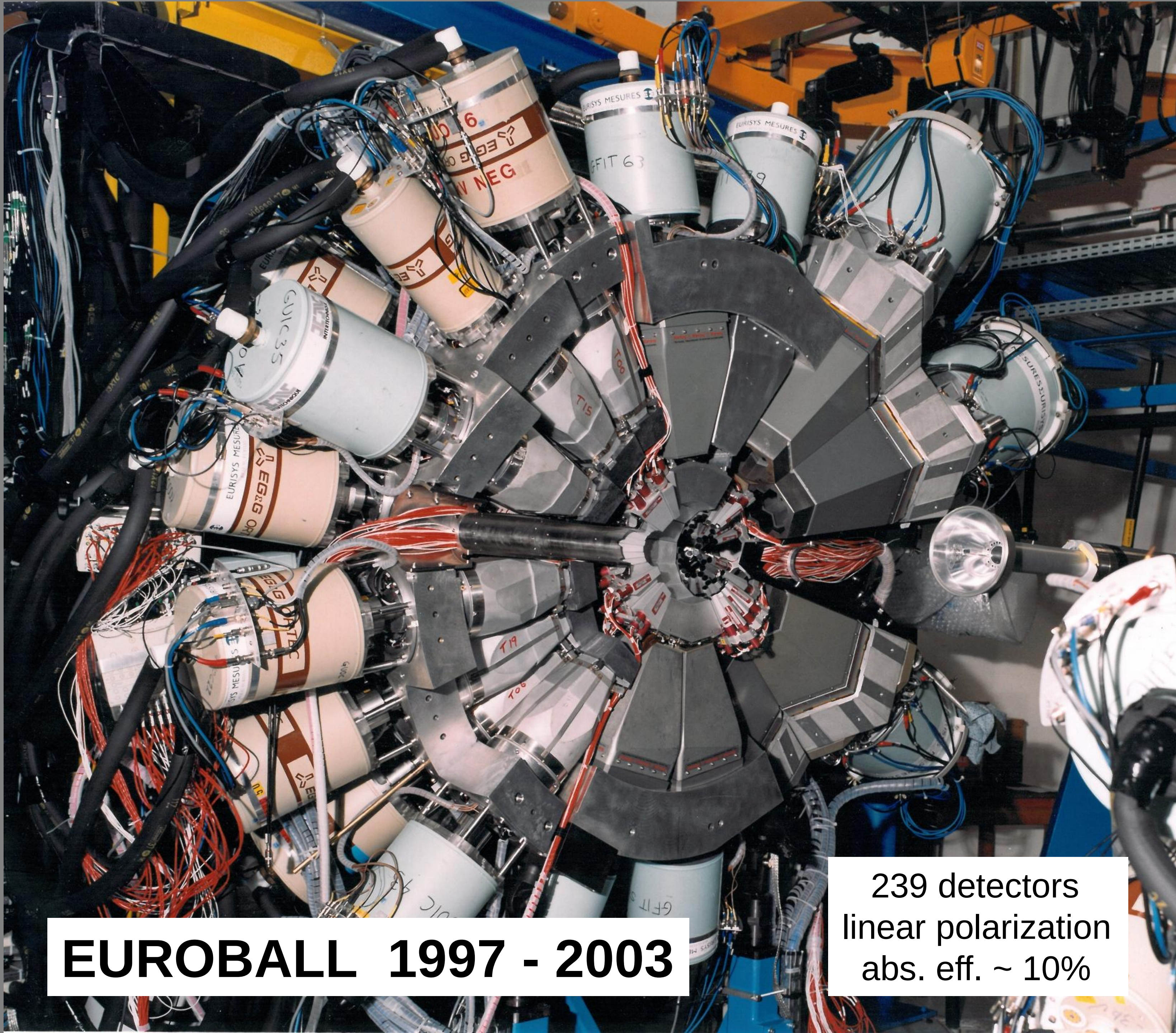






The EUROBALL Cluster Detector

10kg HPGe
rel. efficiency. 600%



EUROBALL 1997 - 2003

239 detectors
linear polarization
abs. eff. ~ 10%

New facilities - new challenges

FAIR
SPIRAL2
SPES
REX-ISOLDE
EURISOL
ECOS

- Low intensity
- High backgrounds
- Large Doppler broadening
- High counting rates
- High γ-ray multiplicities

Need instrumentation

High efficiency
High sensitivity
High throughput
Small solid angle
Ancillary detectors

The last decade: position-sensitive Ge detectors

Position-sensitivity of Ge detectors is based on:

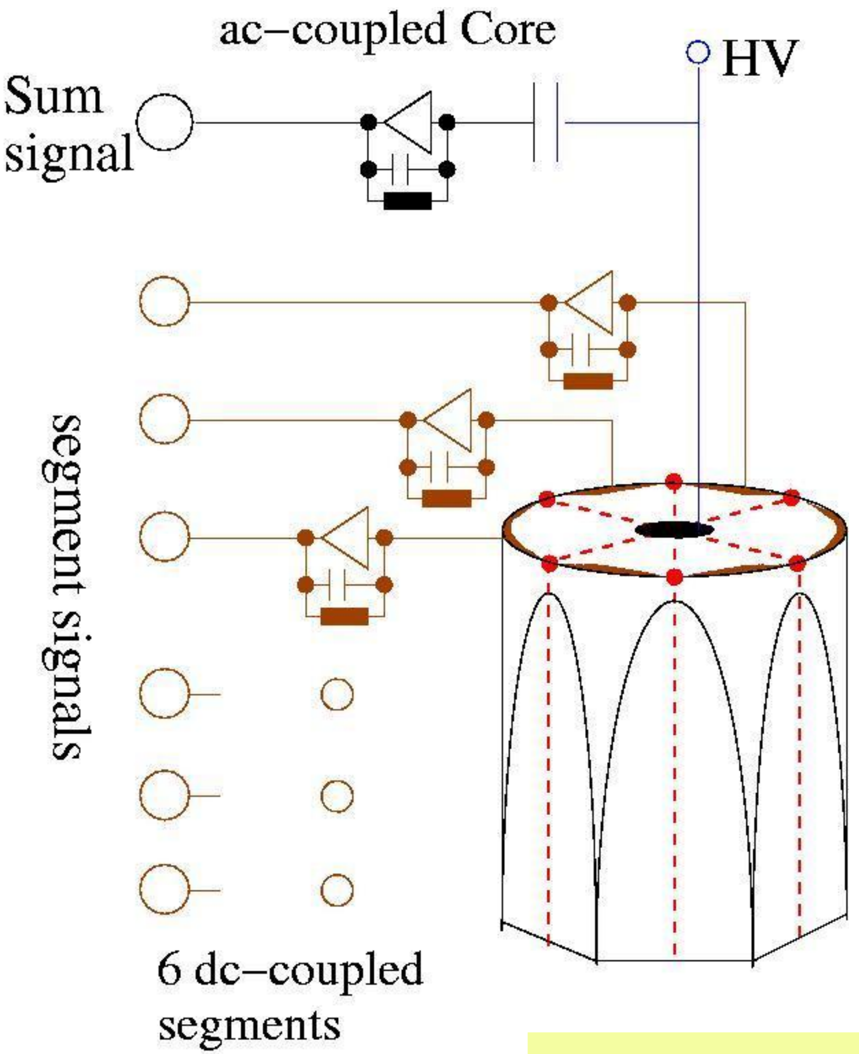
- Segmentation of the detector contacts
- Signal processing with digital electronics
- Pulse shape analysis

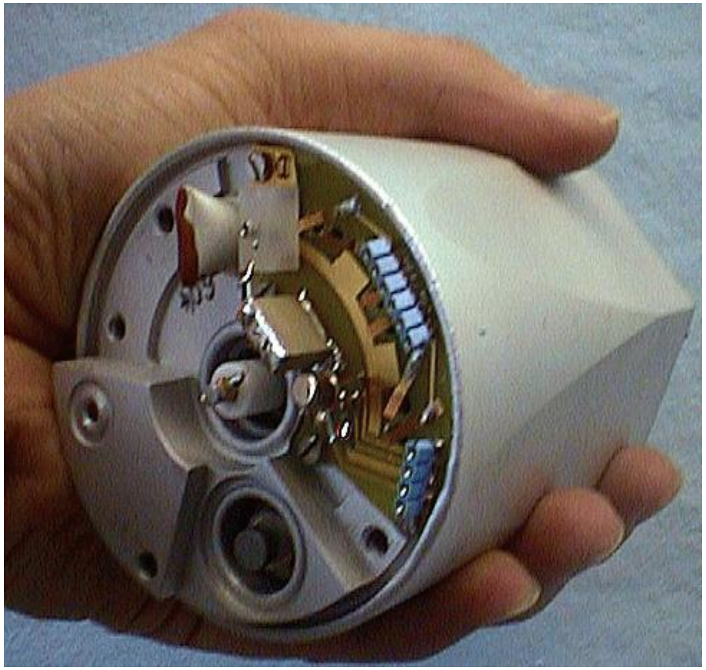
Segmented detectors: SEGA, EXOGAM, TIGRESS

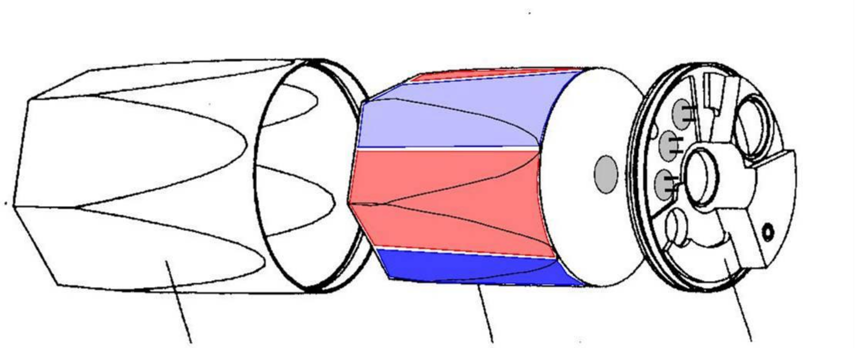
MINIBALL at REX-ISOLDE:

The first array with segmented detectors
and digital signal processing

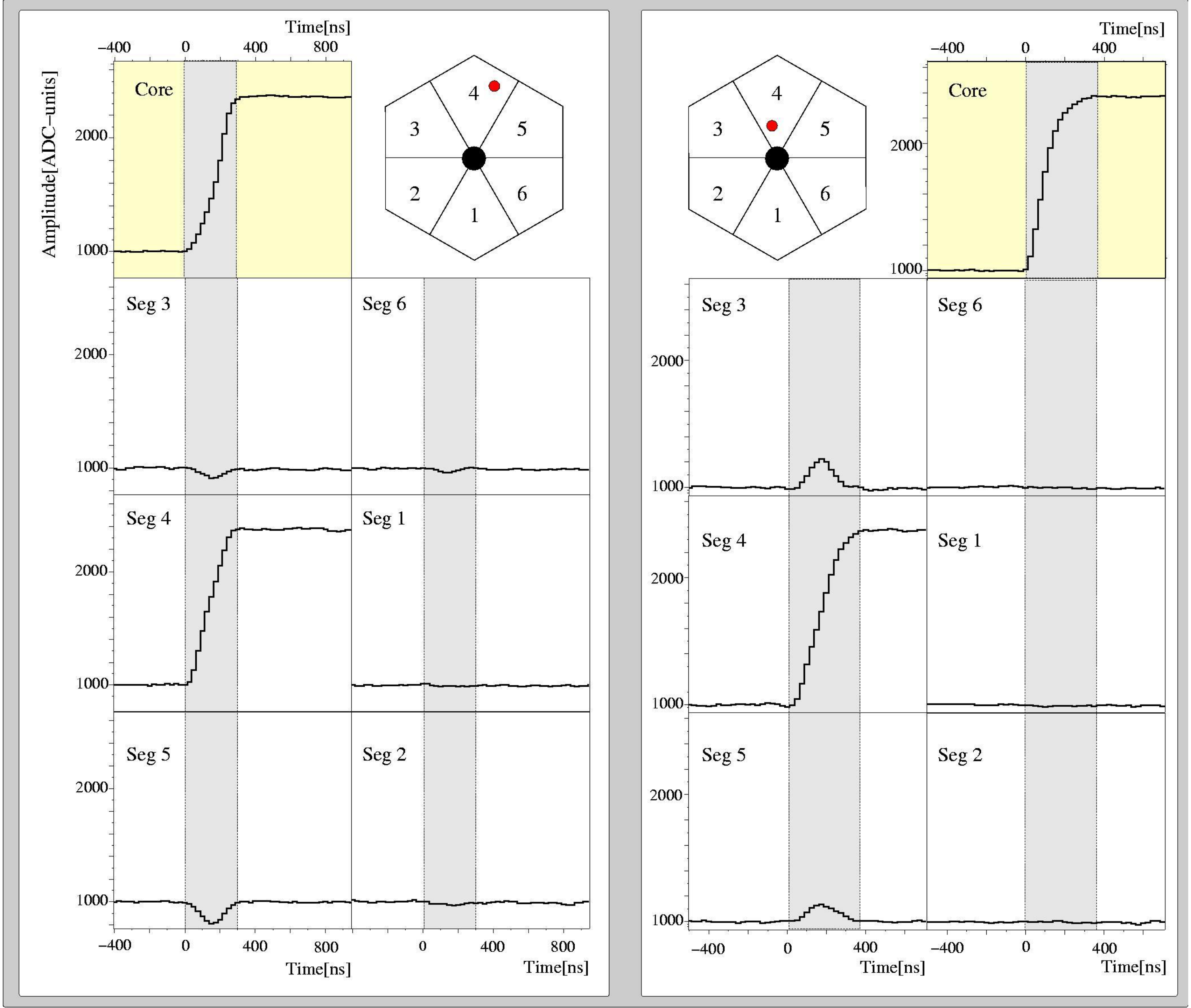
The 6-fold segmented, encapsulated MINIBALL detector







Collaboration: Köln, Heidelberg, München, Leuven



Time[ns]
Amplitude[ADC−units]
Core
Seg 3
Seg 6
Seg 4
Seg 1
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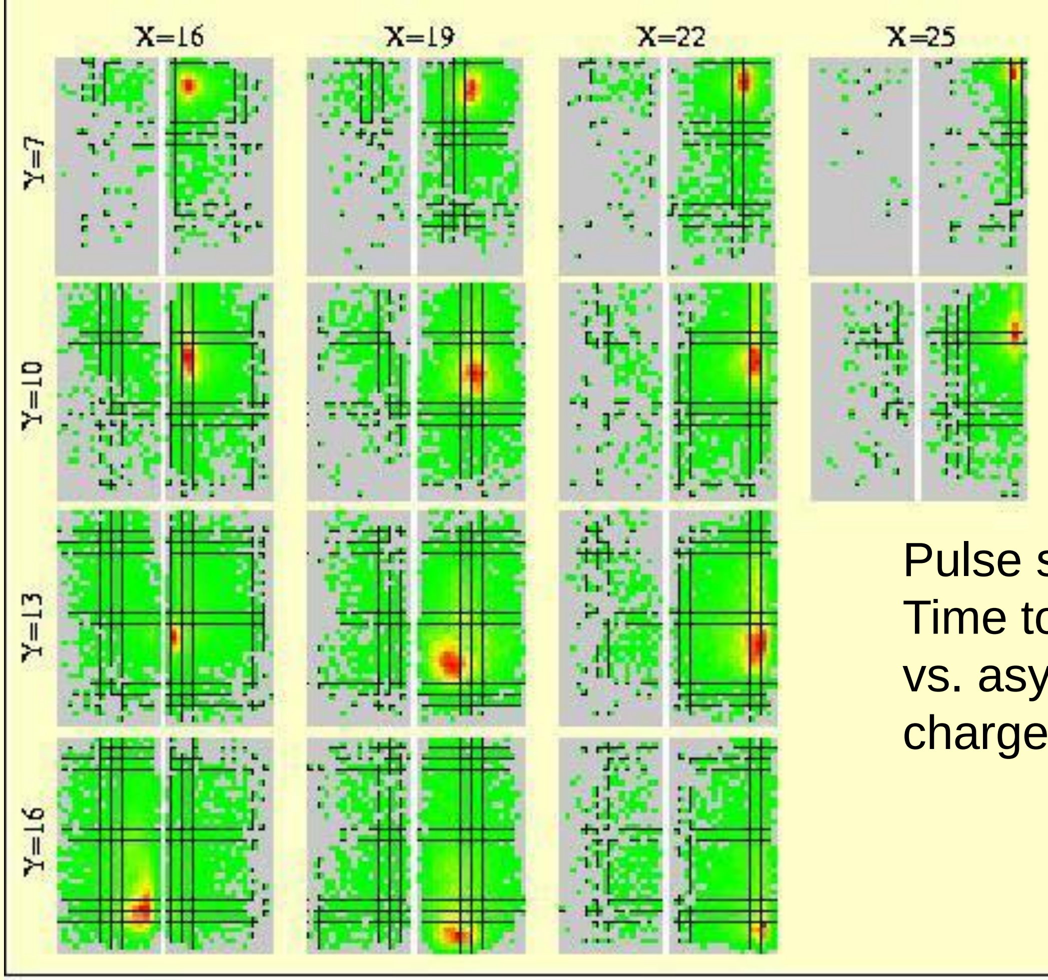
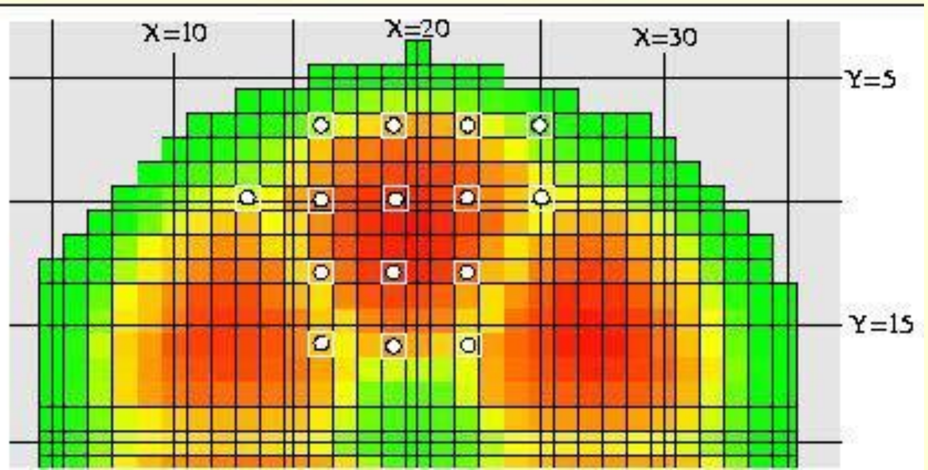
1
2
3
4
5
6
Time[ns]

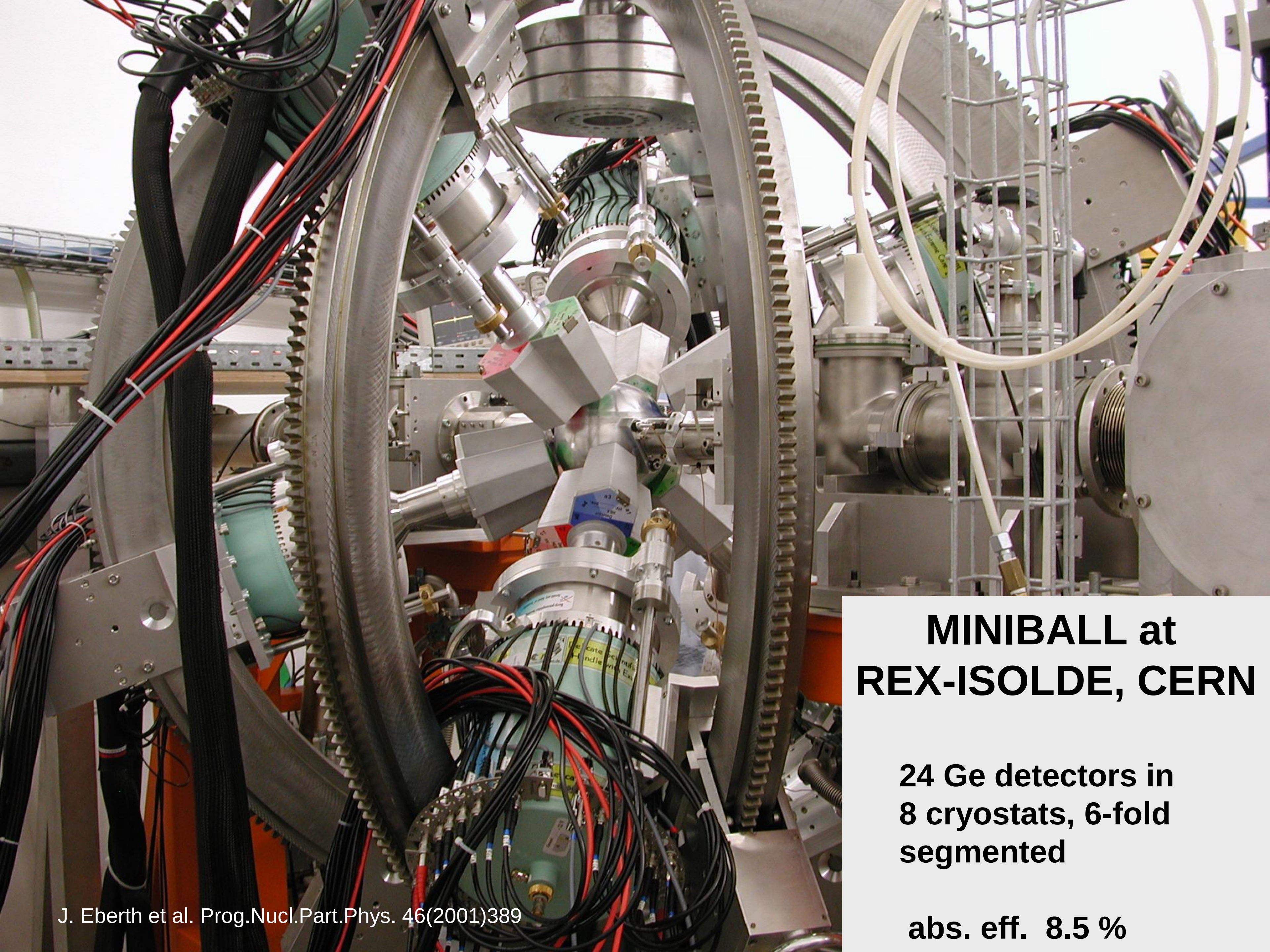


Pulse shape analysis:
Time to steepest slope vs. asymmetry of mirror charges

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

position resolution
~ 5 mm





J. Eberth et al. Prog.Nucl.Part.Phys. 46(2001)389

MINIBALL at REX-ISOLDE, CERN

24 Ge detectors in 8 cryostats, 6-fold segmented

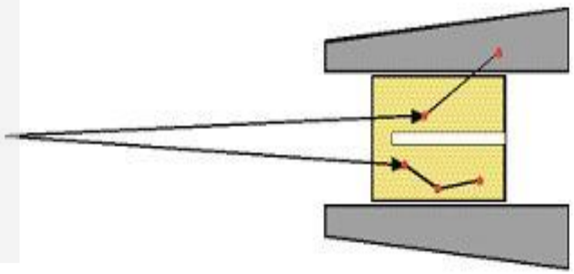
abs. eff. 8.5 %

The idea of γ-ray tracking

Compton Shielded Ge

ε_{ph} ~ 10%
N_{det} ~ 100

Ω ~ 40%
θ ~ 8º



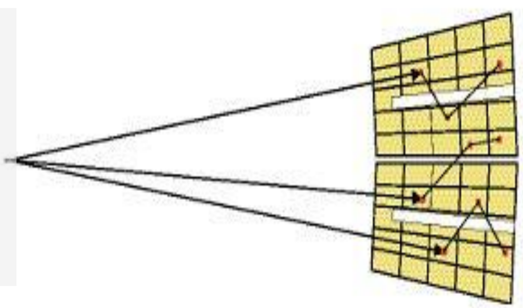
large opening angle means poor energy resolution at high recoil velocity.

Previously scattered gammas were wasted.
Technology is available now to track them.

Ge Tracking Array

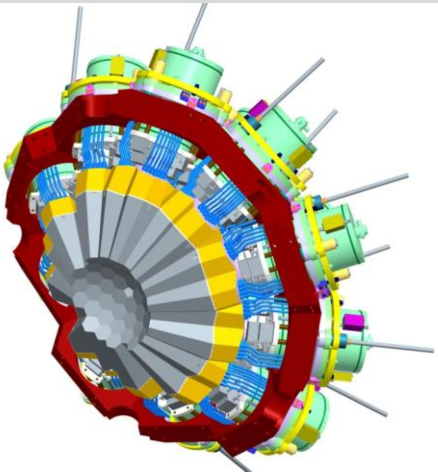
ε_{ph} ~ 50%
N_{det} ~ 100

Ω ~ 80%
θ ~ 1º



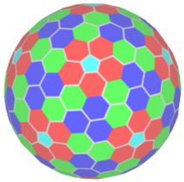
Combination of:

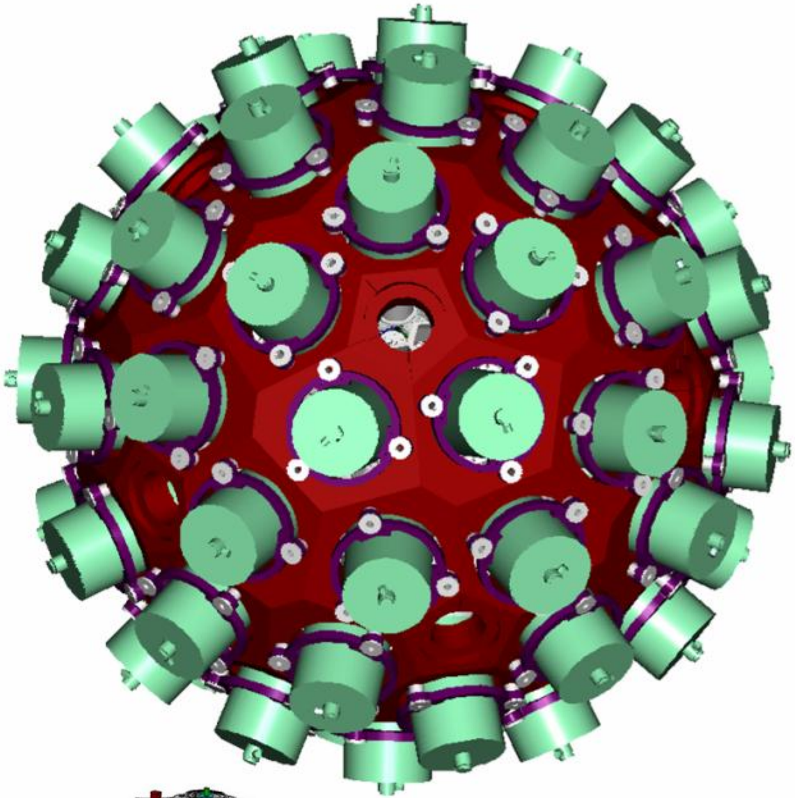
- segmented detectors
- digital electronics
- pulse processing
- tracking the γ-rays



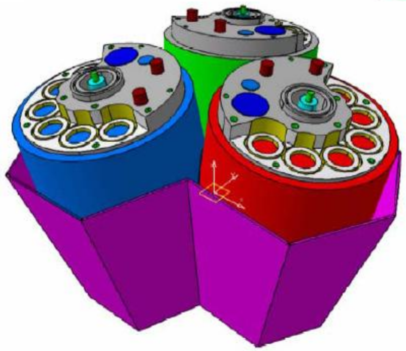
AGATA / GRETA

AGATA



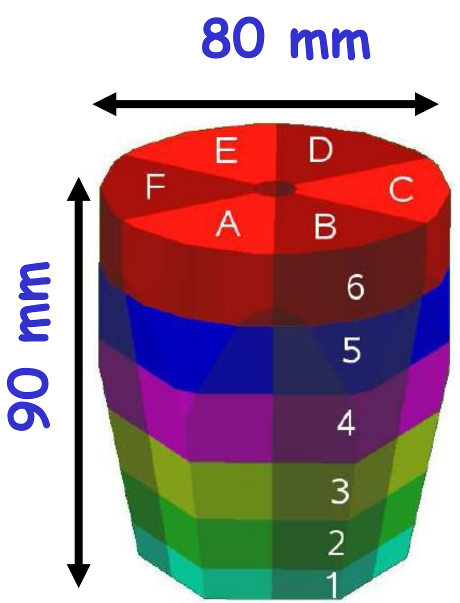


180 hexagonal crystals	3 shapes
60 triple-clusters	all equal
Inner radius (Ge)	23.5 cm
Amount of germanium	362 kg
Solid angle coverage	82 %
36-fold segmentation	6480 segments
Singles rate	~50 kHz
Efficiency:	43% (M_γ=1) 28% (M_γ=30)
Peak/Total:	58% (M_γ=1) 49% (M_γ=30)



6660 high-resolution digital electronics channels
Pulse Shape Analysis → position sensitive operation mode
γ-ray tracking algorithms to achieve maximum efficiency.
Coupling to ancillary detectors for added selectivity

AGATA detectors and the AGATA triple-cluster



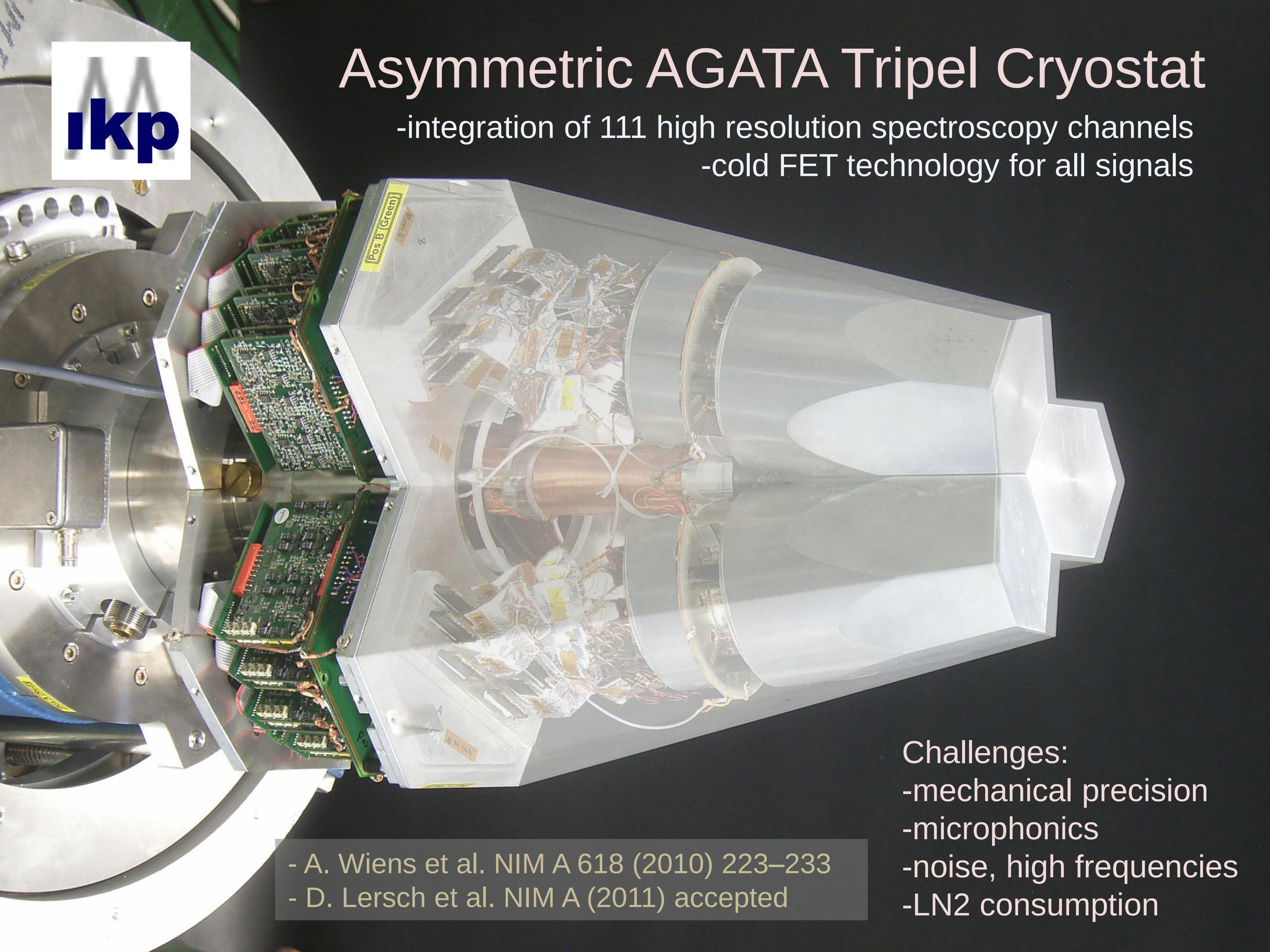
6x6 segmented cathode

Symmetric detectors
- 3 in use since 6 years
- Used in single cryostats or as a triple cluster

Asymmetric detectors
- 31 ordered
- 15 accepted
- 4 clusters operational

Asymmetric AGATA Tripel Cryostat

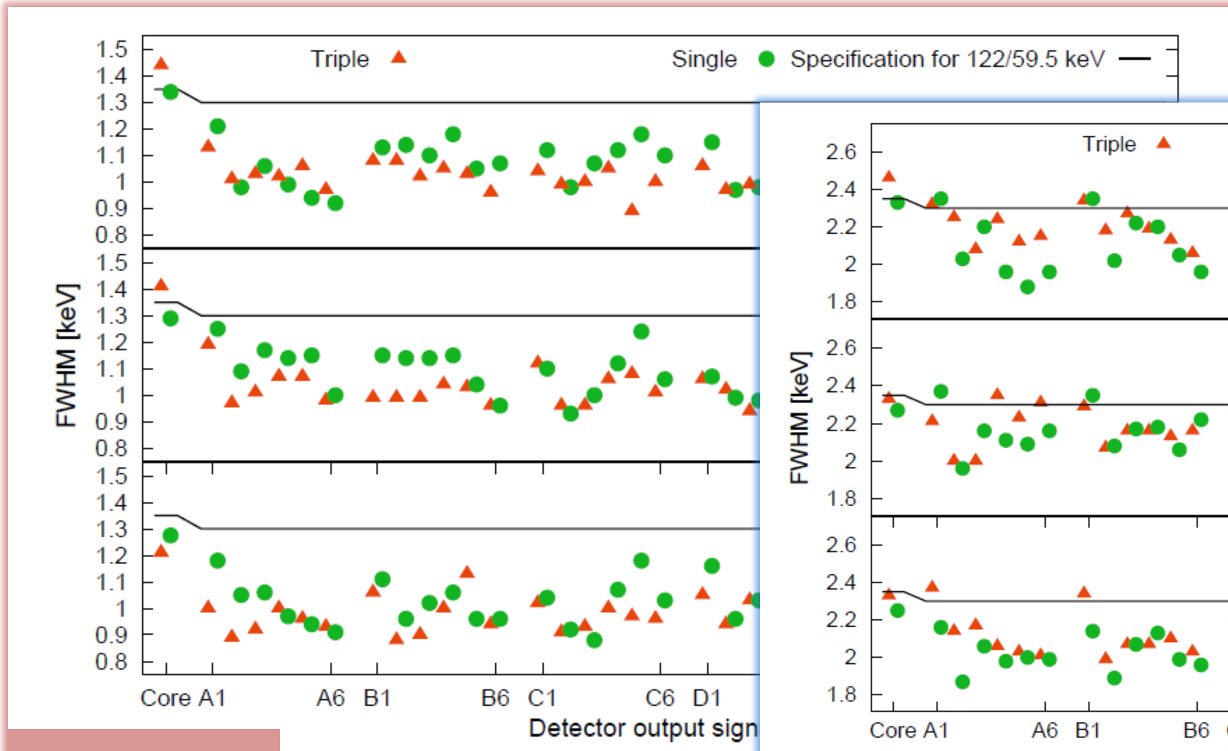
-integration of 111 high resolution spectroscopy channels
-cold FET technology for all signals



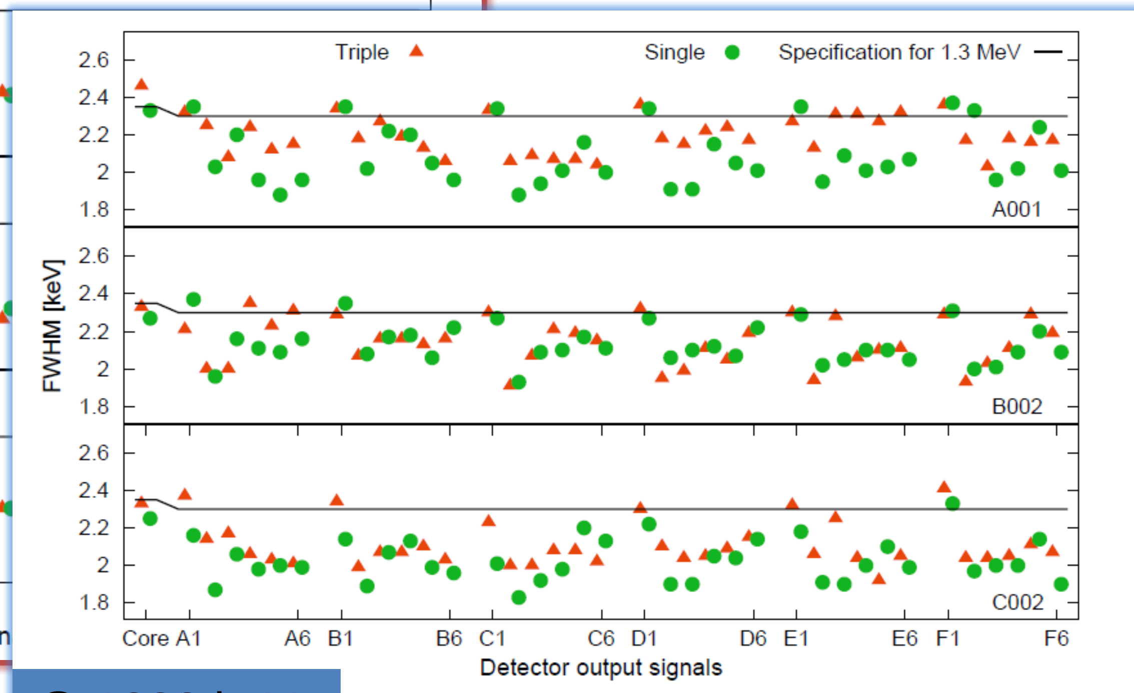
Challenges:
-mechanical precision
-microphonics
-noise, high frequencies
-LN2 consumption

- A. Wiens et al. NIM A 618 (2010) 223–233
- D. Lersch et al. NIM A (2011) accepted

Performance: Energy resolution



@ 60 keV



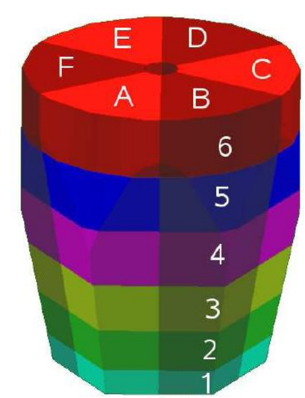
@ 1333 keV

Averages of the segment resolutions
@ **60 keV :**

A001:	1011 +/- 53 eV
B002:	1039 +/- 70 eV
C002:	965 +/- 63 eV

Averages of the segment resolutions measured in Köln and Legnaro
@ 1333 keV :

	IKP	/	Legnaro
A001:	2,19 keV	/	2,00 keV
B002:	2,09 keV	/	1,98 keV
C002:	2,1 keV	/	1,94 keV

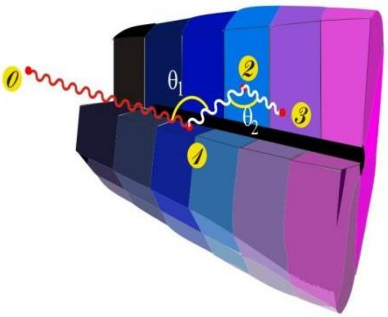


Segment labelling

Ingredients of Gamma-Ray Tracking

1

Highly segmented
HPGe detectors



2

Digital electronics
to record and
process segment signals

3

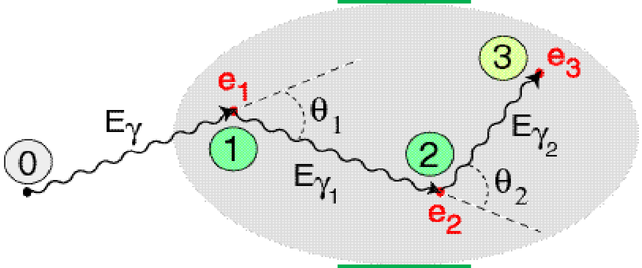
Pulse Shape Analysis
to decompose
recorded waves

Identified
interaction points

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

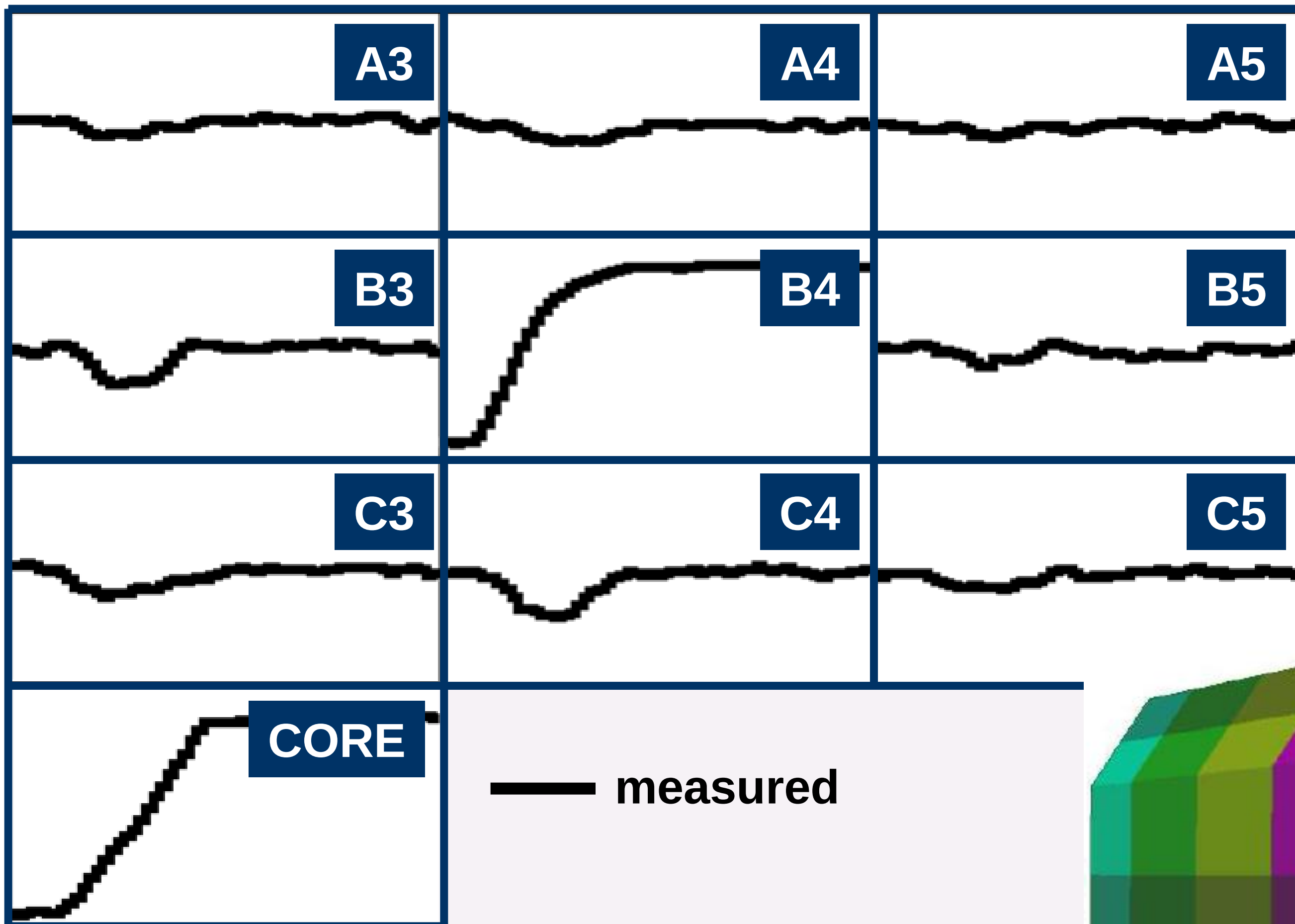
4

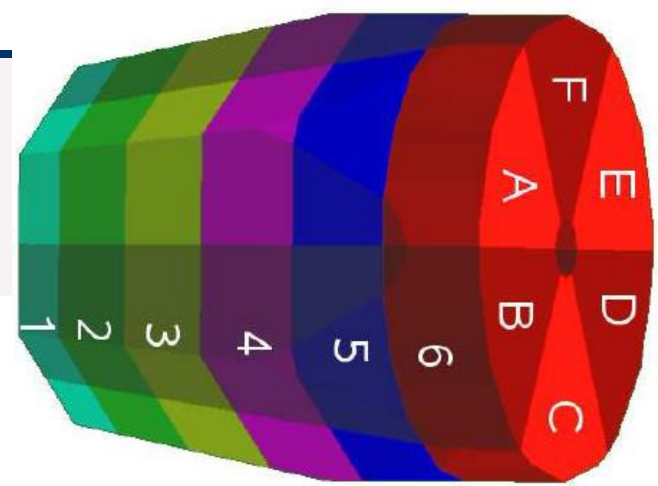
Reconstruction of tracks
evaluating permutations
of interaction points



Reconstructed gamma-rays

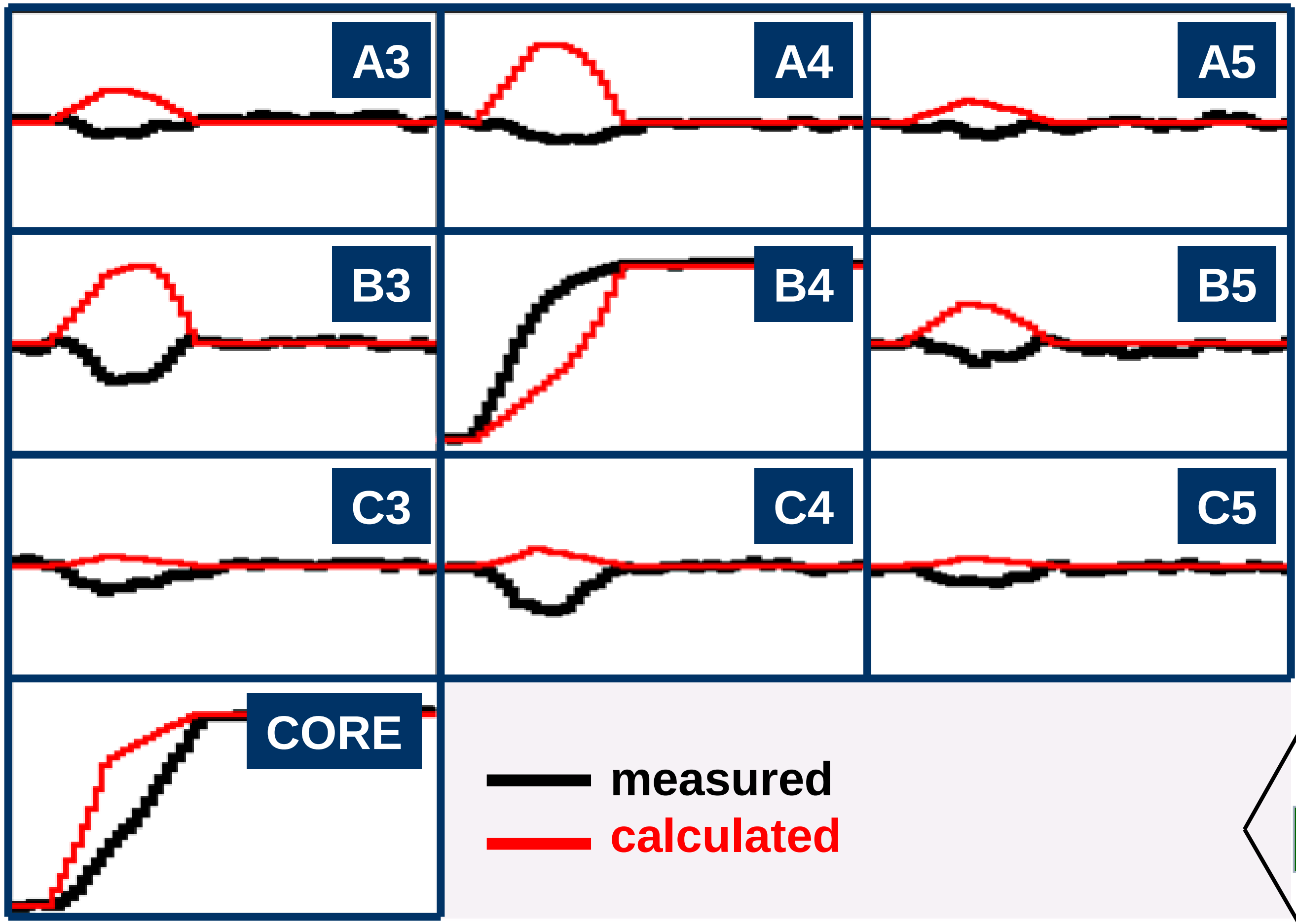
Pulse Shape Analysis concept

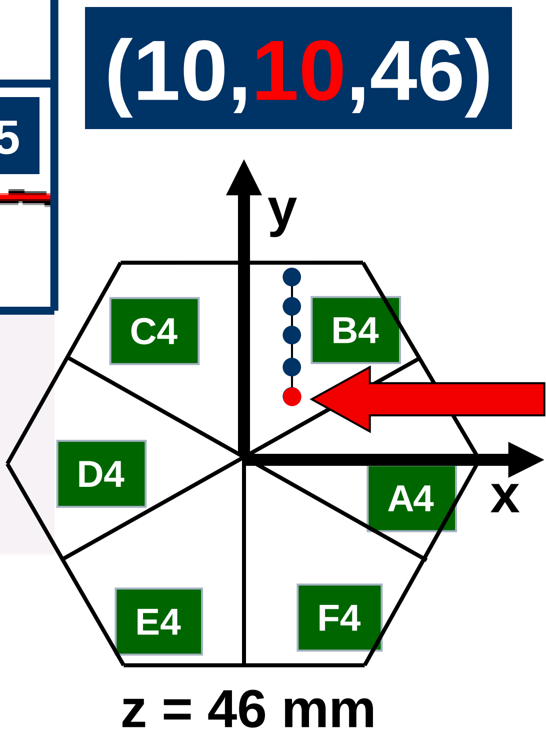




791 keV deposited in segment B4

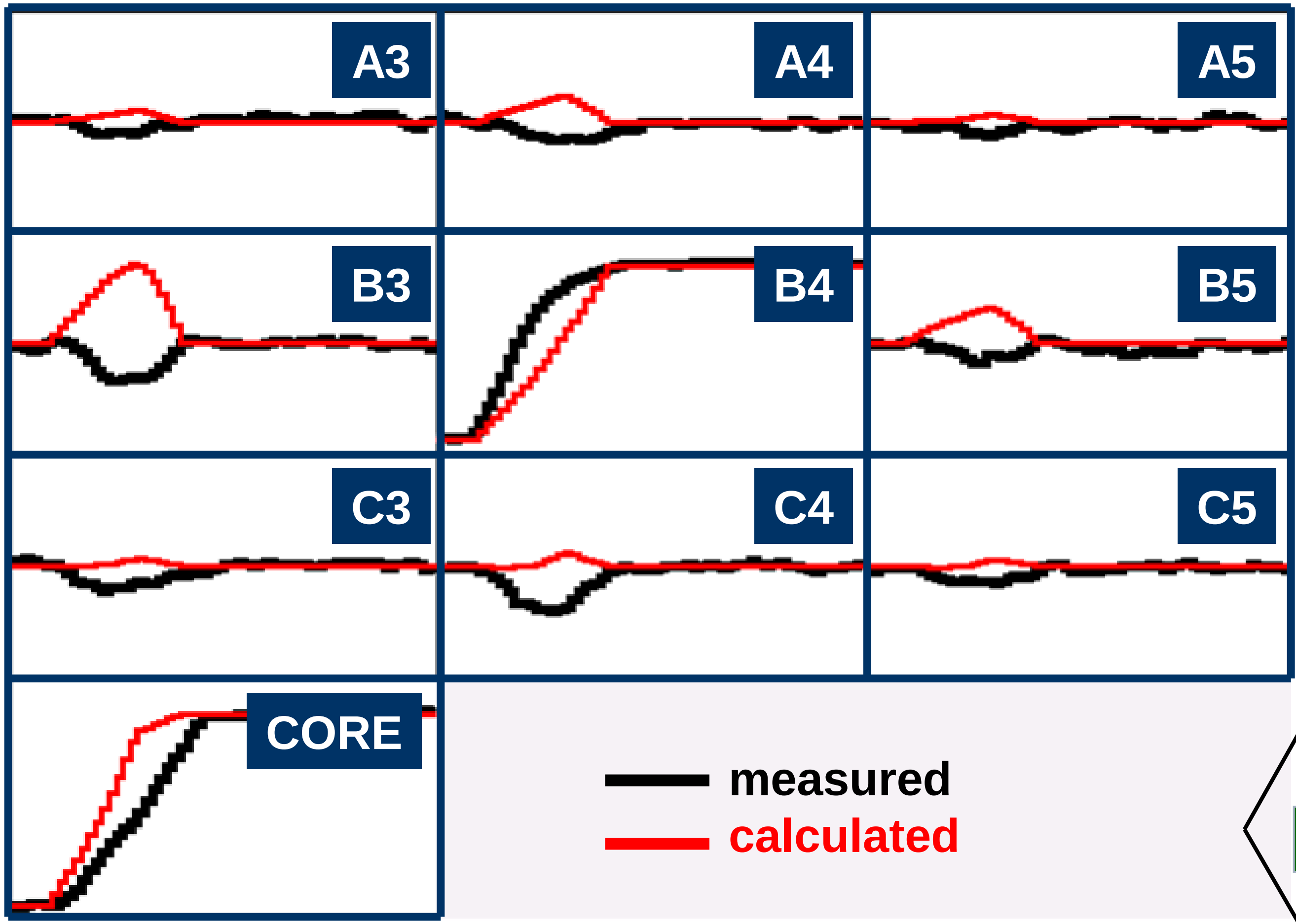
Pulse Shape Analysis concept





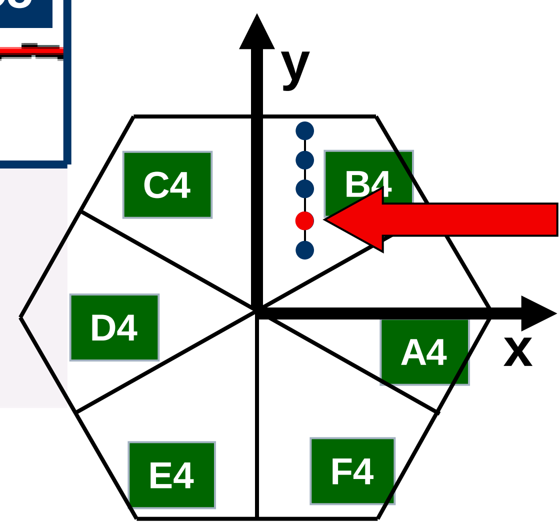
791 keV deposited in segment B4

Pulse Shape Analysis concept



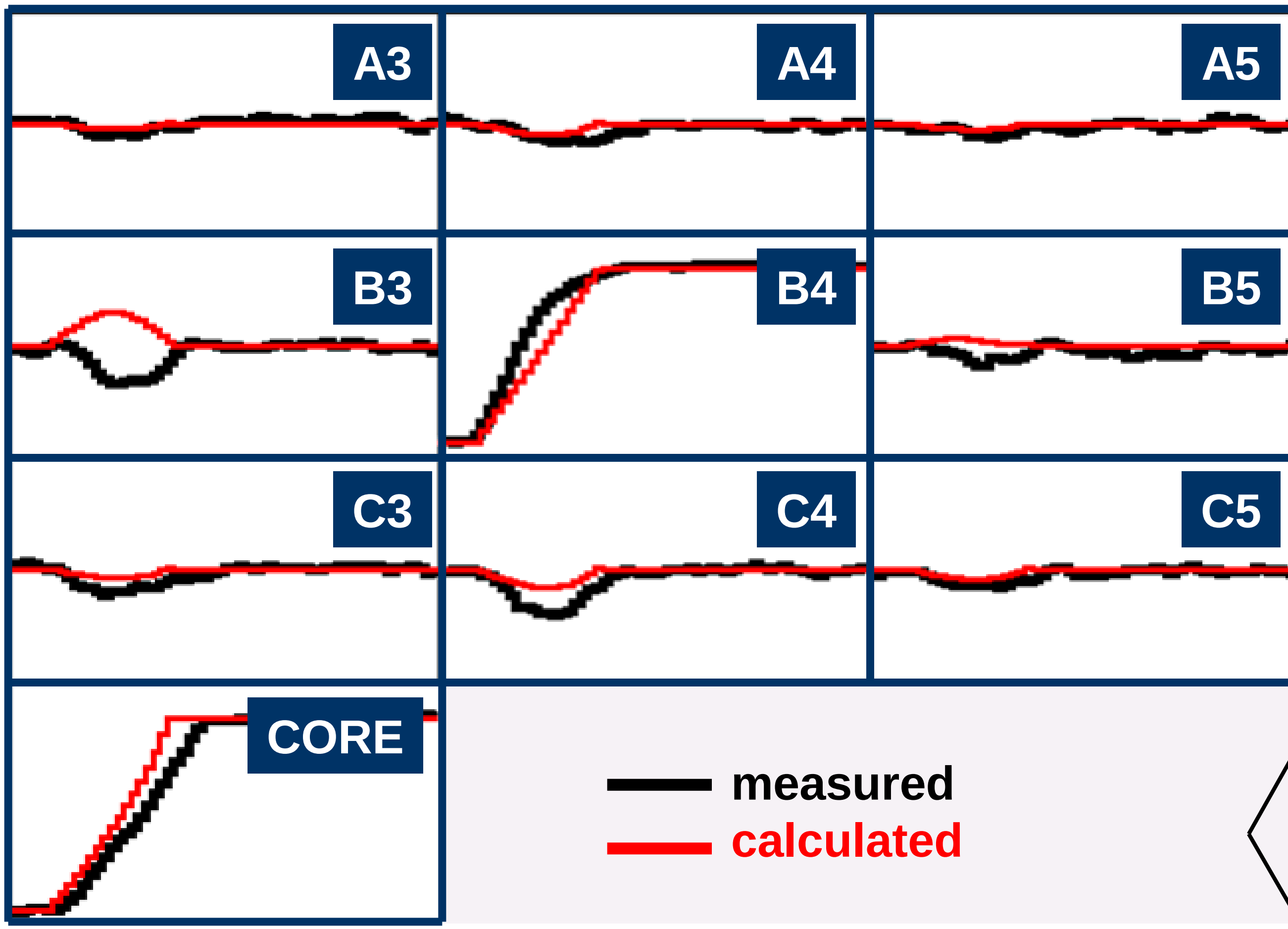
791 keV deposited in segment B4

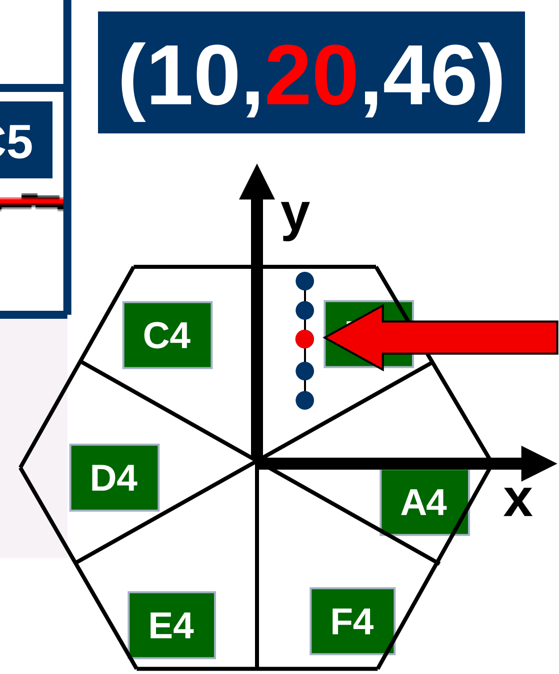
(10,15,46)



z = 46 mm

Pulse Shape Analysis concept

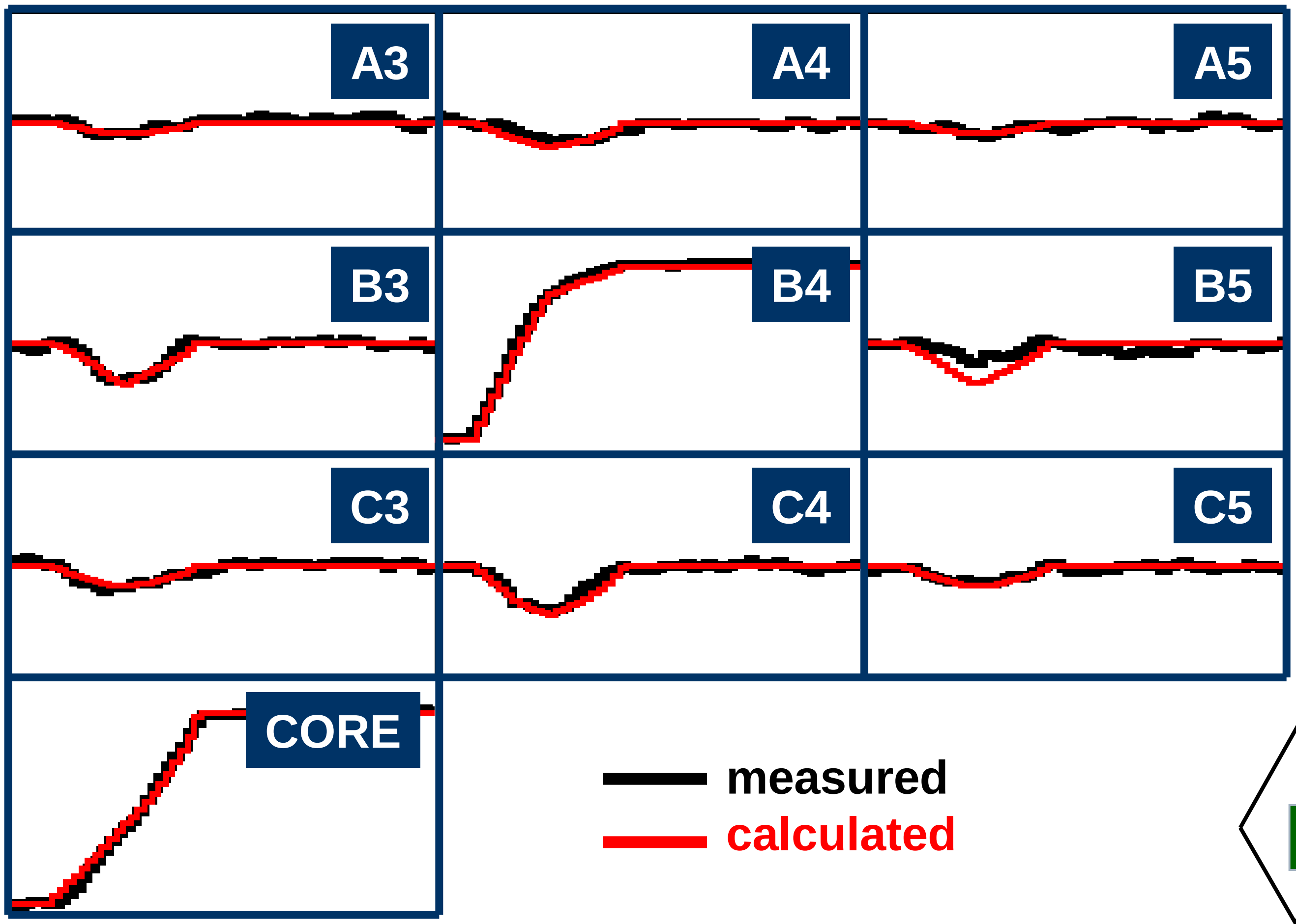


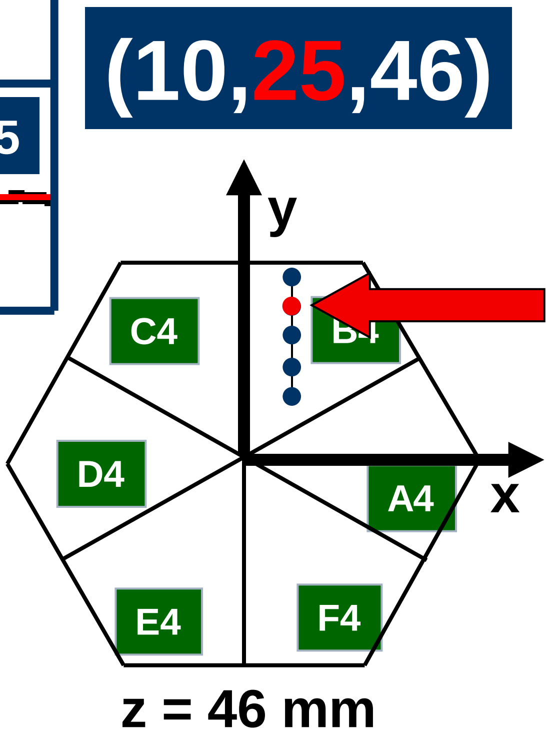


z = 46 mm

791 keV deposited in segment B4

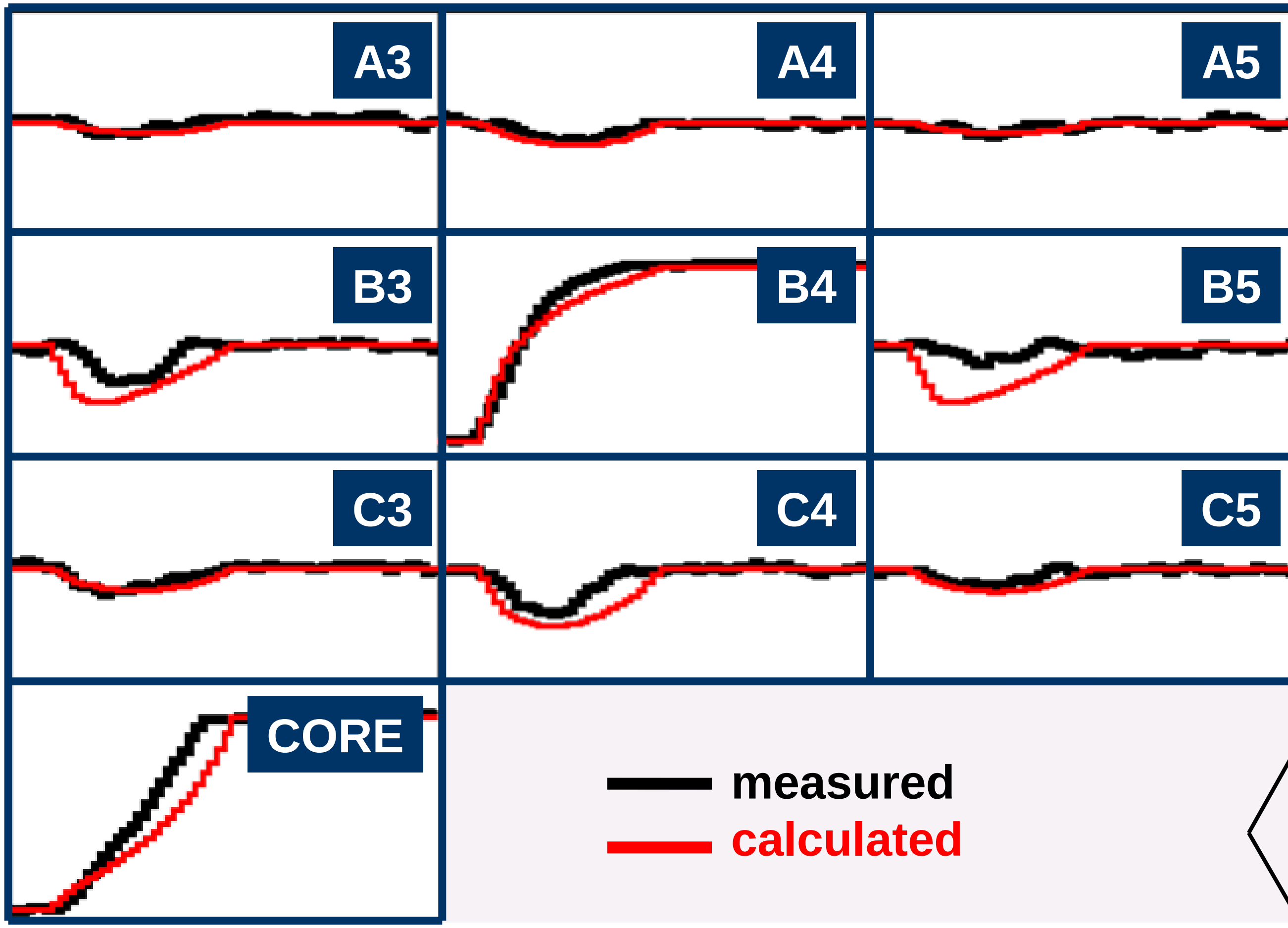
Pulse Shape Analysis concept



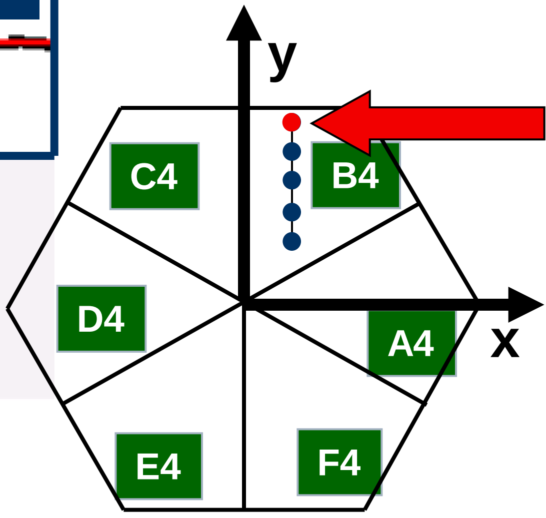


791 keV deposited in segment B4

Pulse Shape Analysis concept



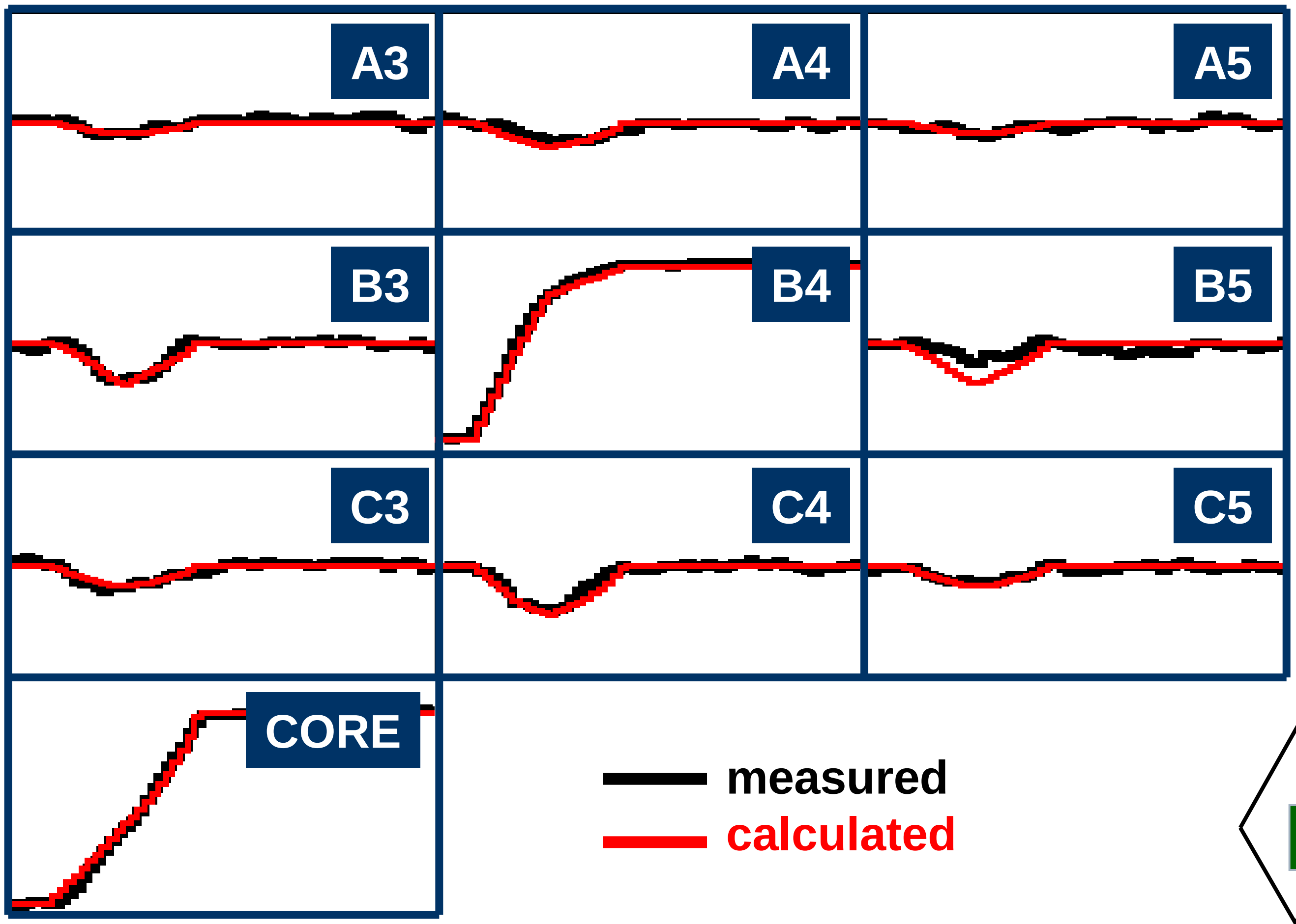
(10,30,46)



z = 46 mm

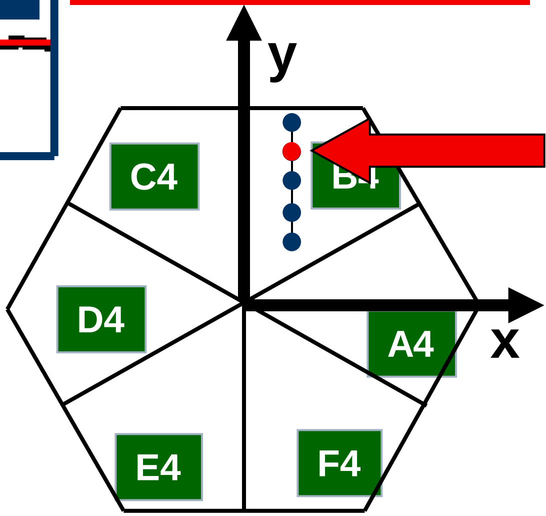
791 keV deposited in segment B4

Pulse Shape Analysis concept



Result of *Grid Search* Algorithm

(10,25,46)

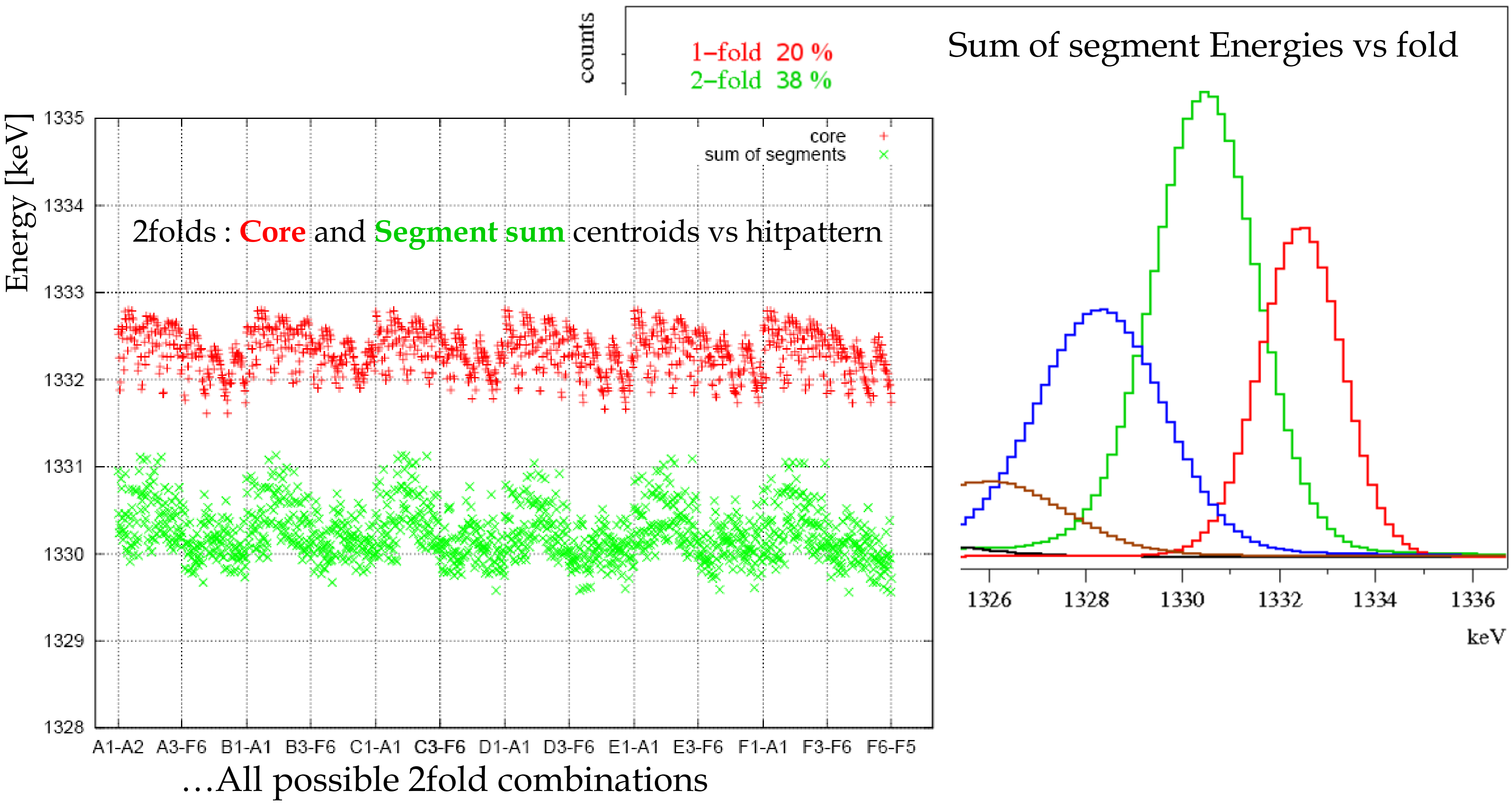


z = 46 mm

791 keV deposited in segment B4

Cross talk correction: Motivation

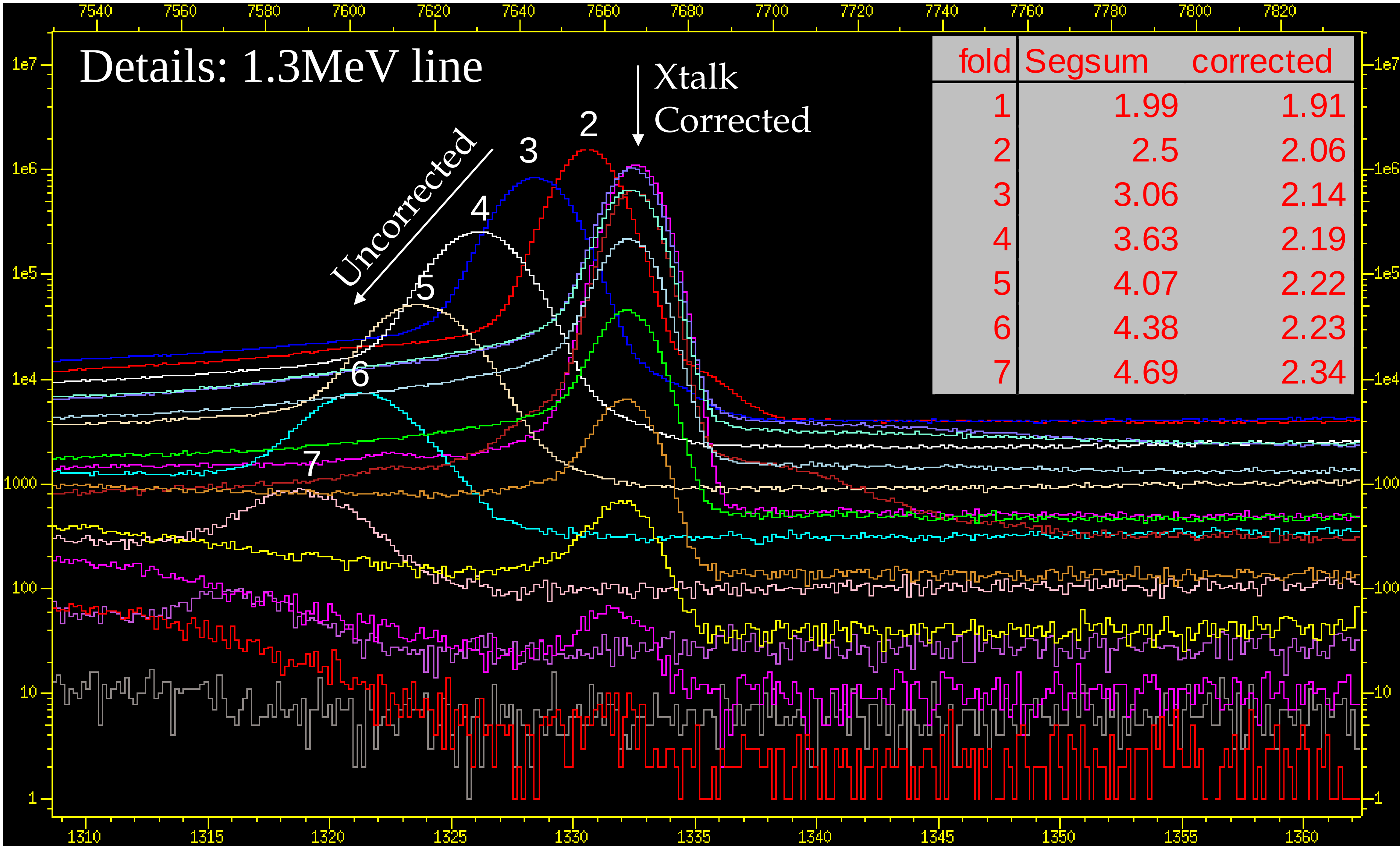
- Crosstalk is present in <u>every</u> segmented detector
- Creates strong energy shifts proportional to fold
- Tracking needs <u>segment energies</u> !



On line Cross Talk Correction

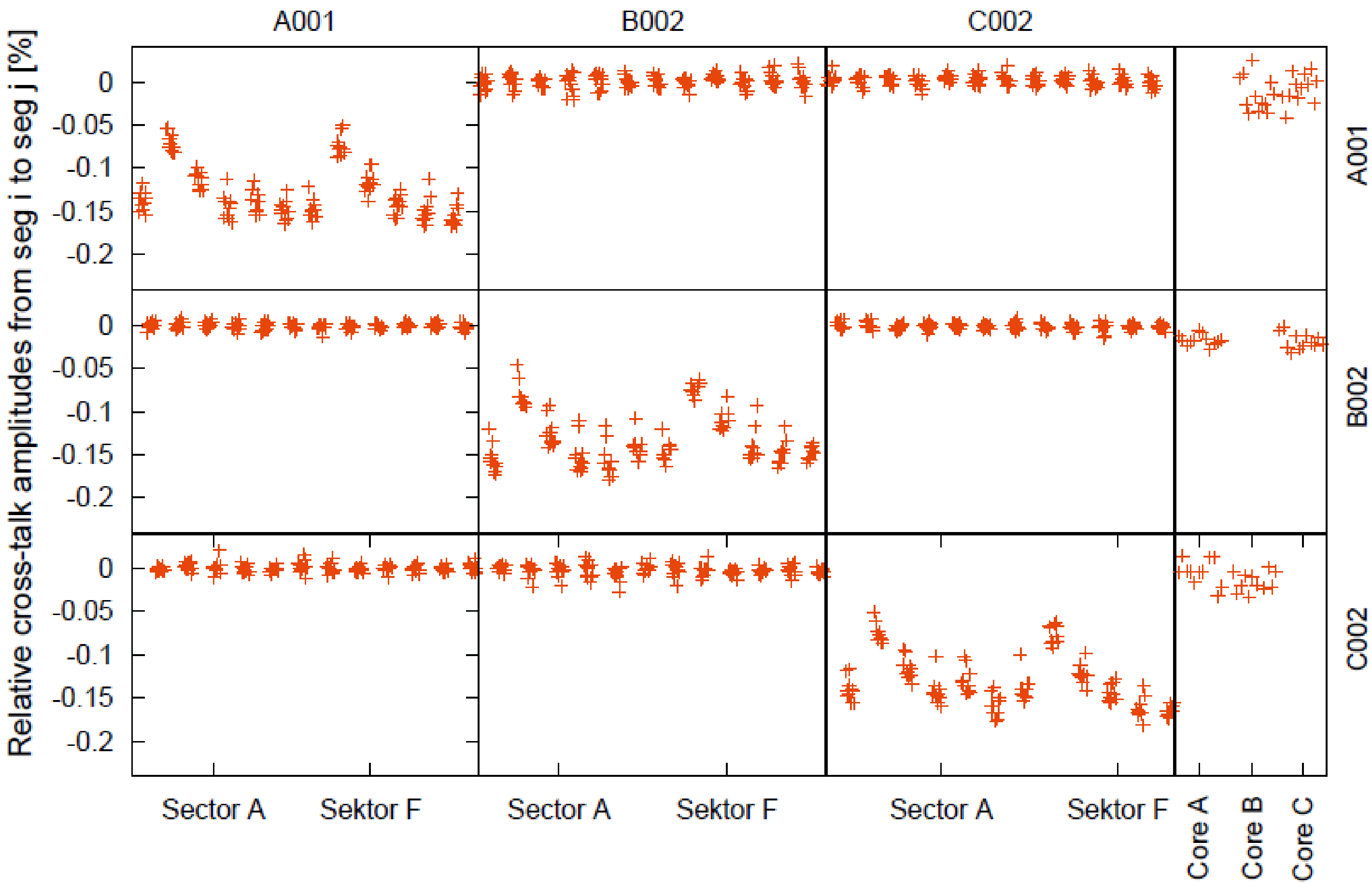
B. Bruyneel et al., NIM A 599 (2009) 196

FWHM 60keV: 1.20 → 1.02 !



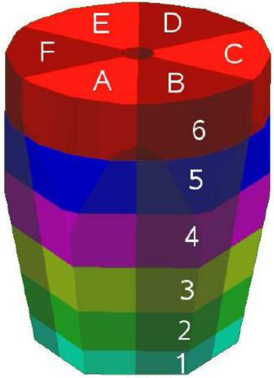
fold	Segsum	corrected
1	1.99	1.91
2	2.5	2.06
3	3.06	2.14
4	3.63	2.19
5	4.07	2.22
6	4.38	2.23
7	4.69	2.34

Performance: Crosstalk

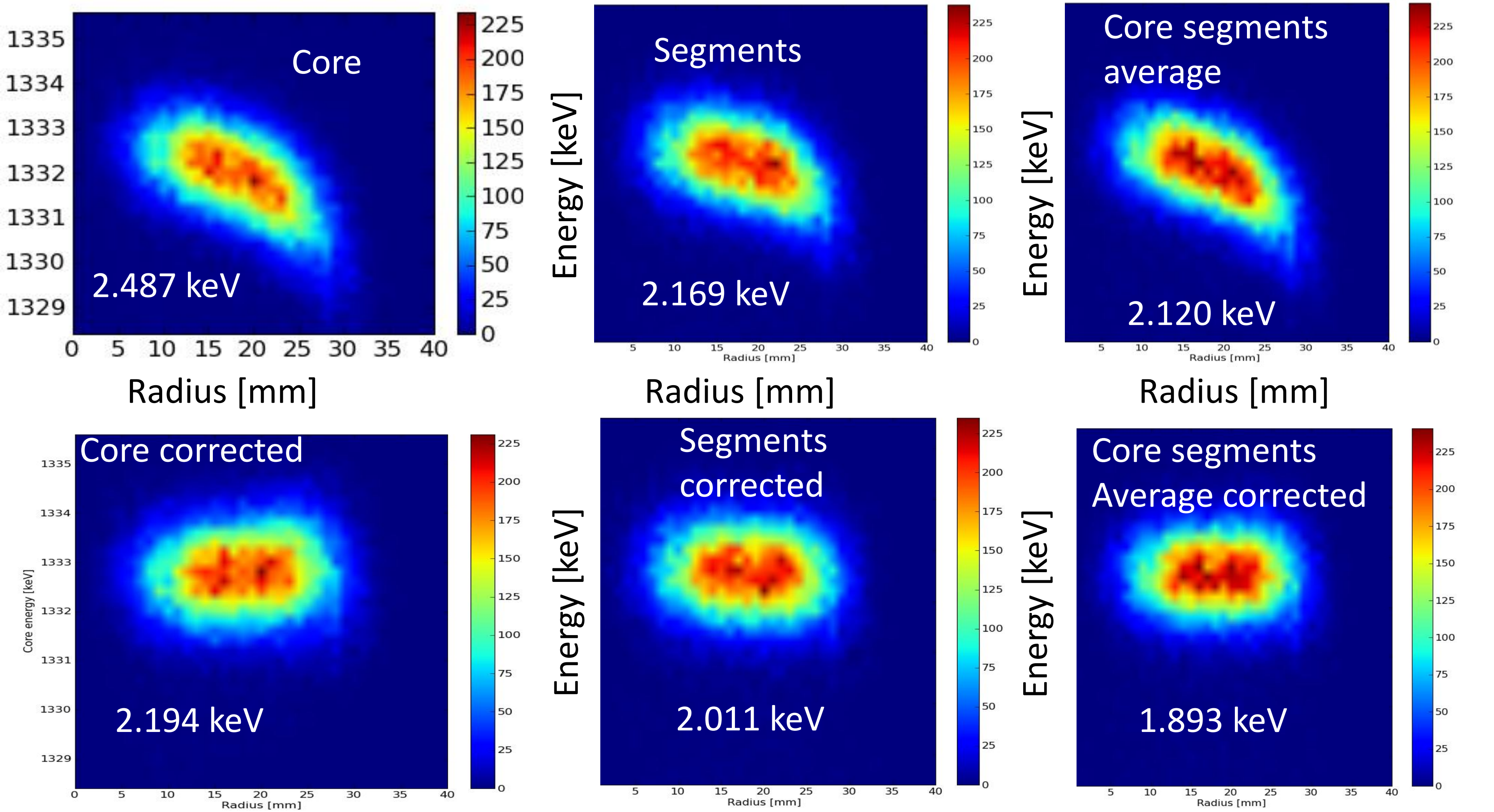


- No crosstalk observed between detectors
- Within one detector, the theoretical crosstalk limit is reached
- Online cross talk correction implemented

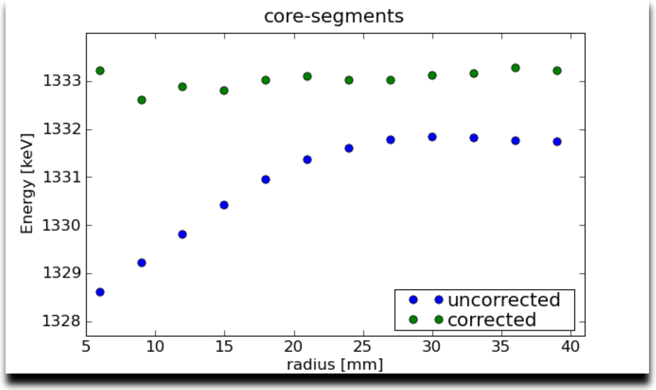
All n-type Ge detectors suffer from electron trapping.
Knowing the interaction position and charge collection path
The trapping effects can be corrected.

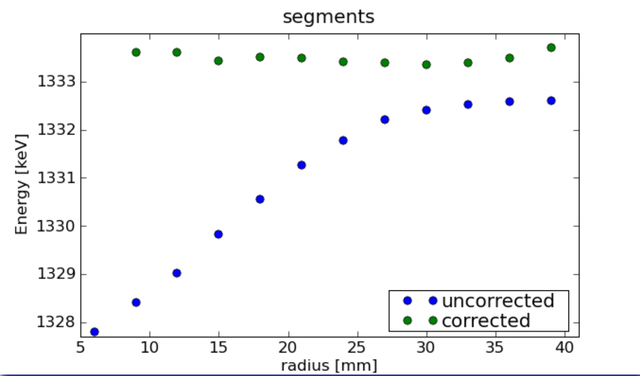


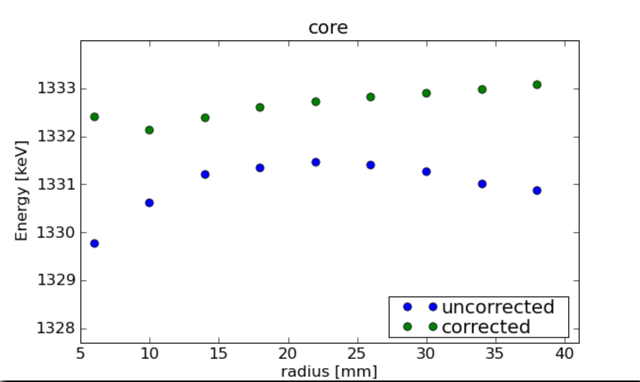
Example: Ring 1 energy @ 1.3 MeV

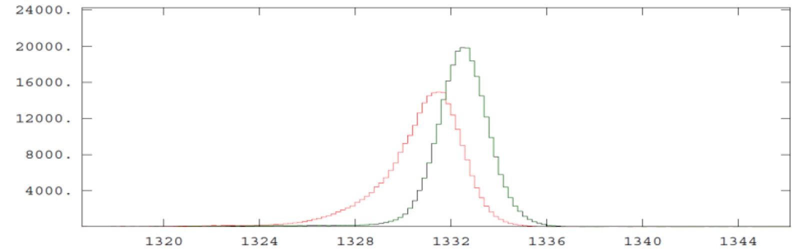


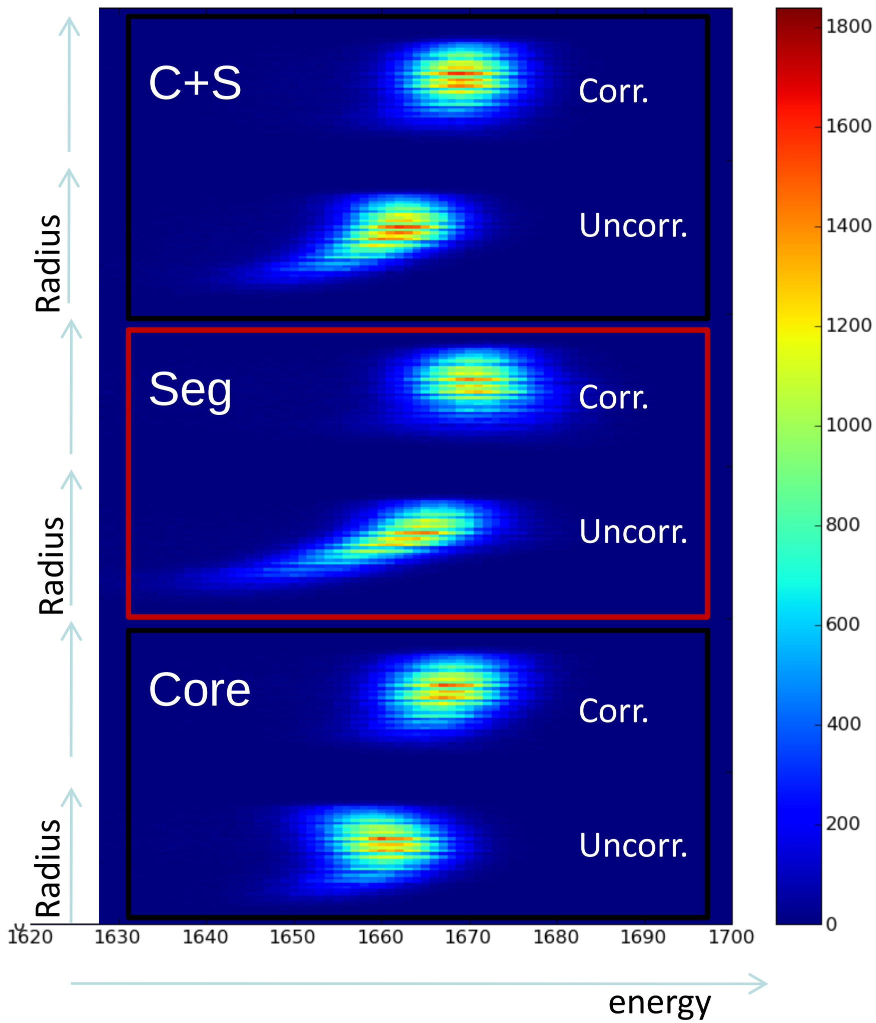
Correction of neutron damage





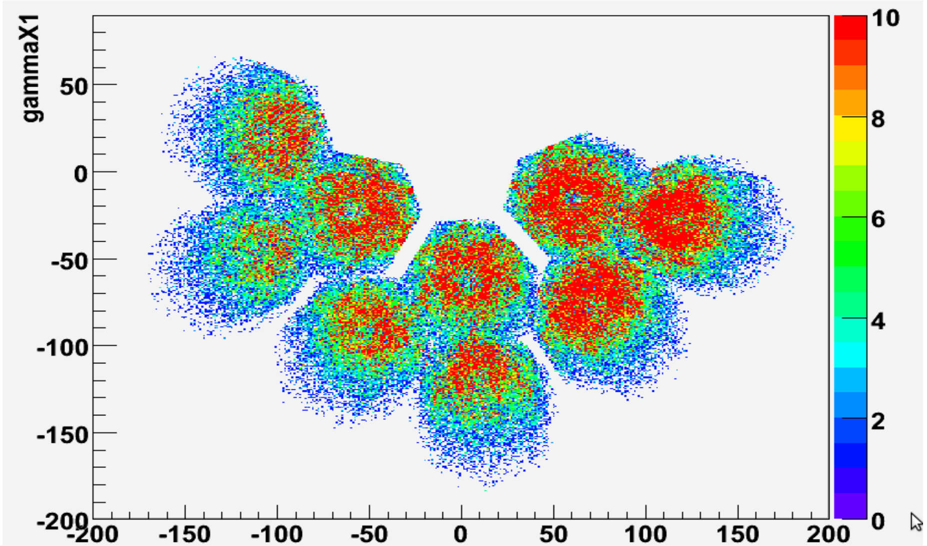


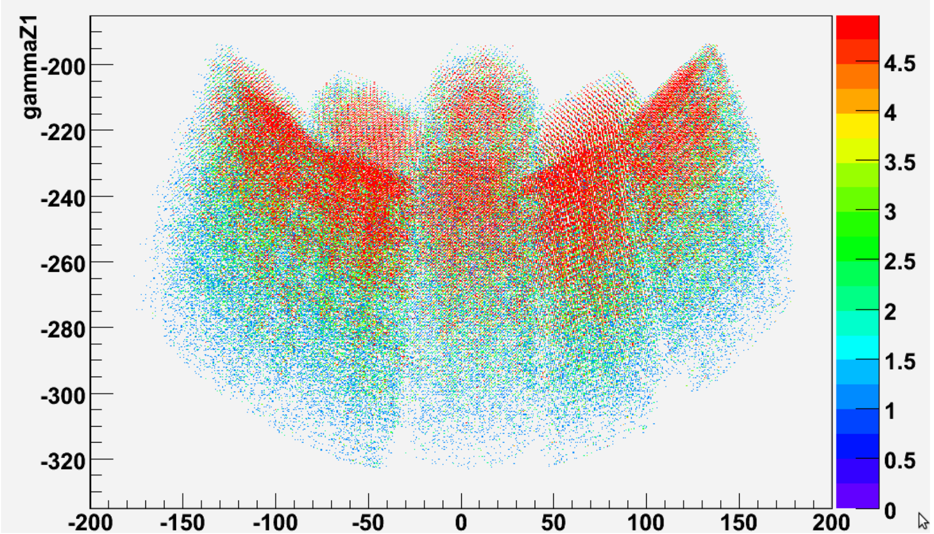




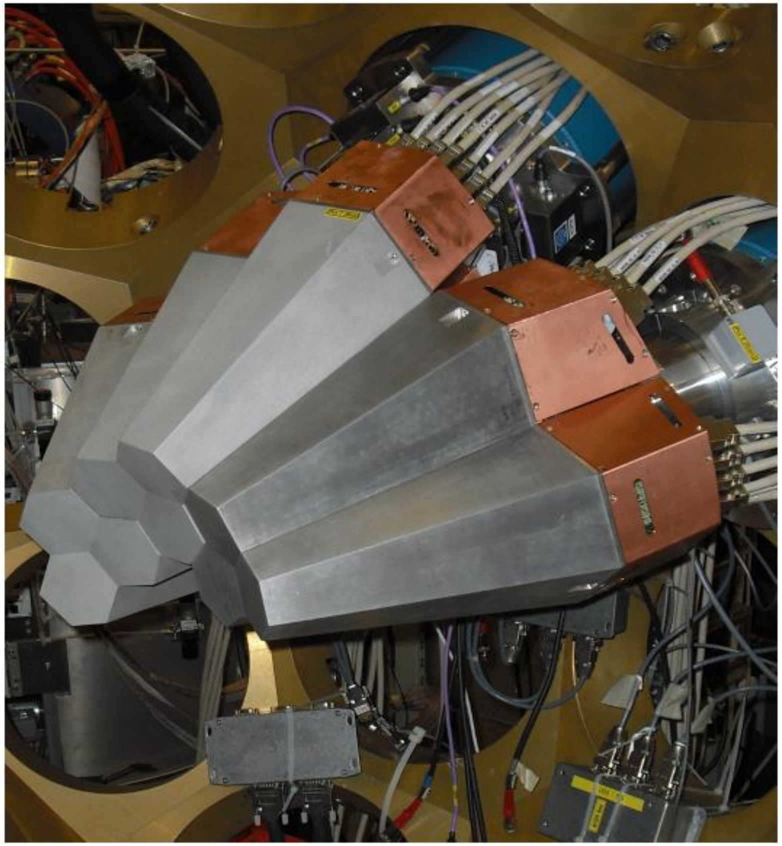
FWHM 1.3MeV	FWTM / FWHM
2.06	1.91
2.44	1.83
2.51	1.83
2.88	2.34
2.30	1.83
2.34	1.83

AGATA online





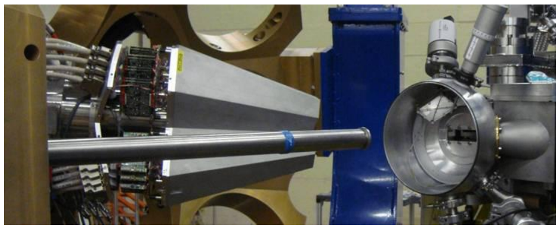
1st experiment with AGATA (18/02/10)

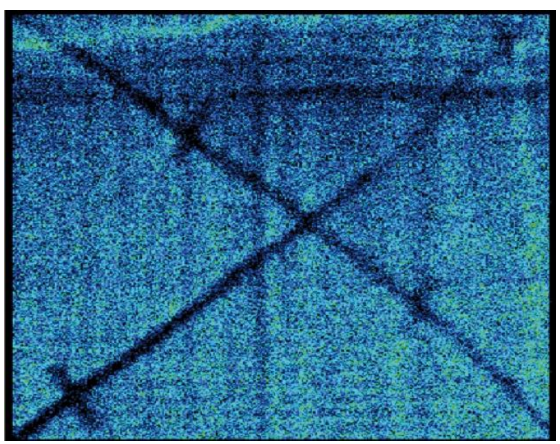


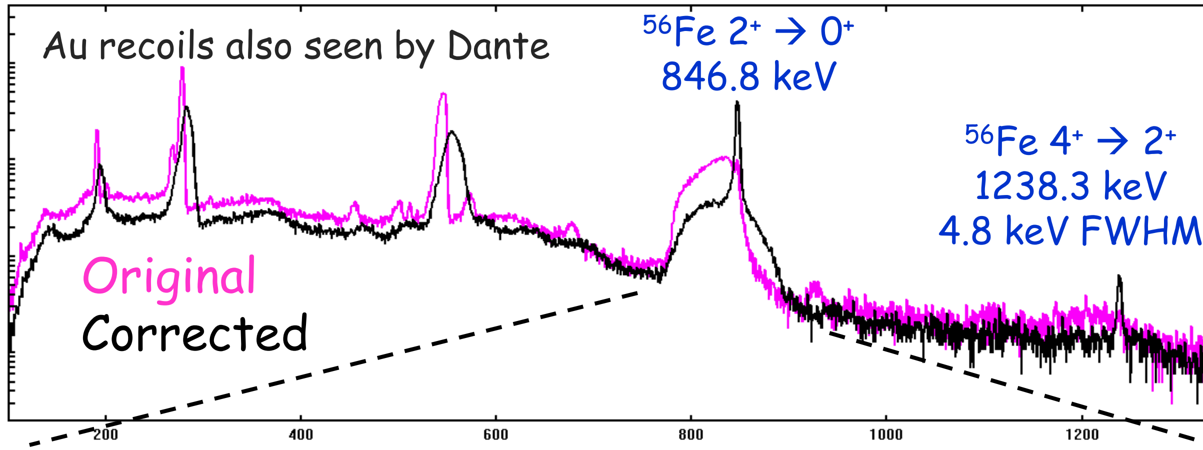
- < 5mm FWHM resolution obtained
- psa online at rates > 5kHz per crystal

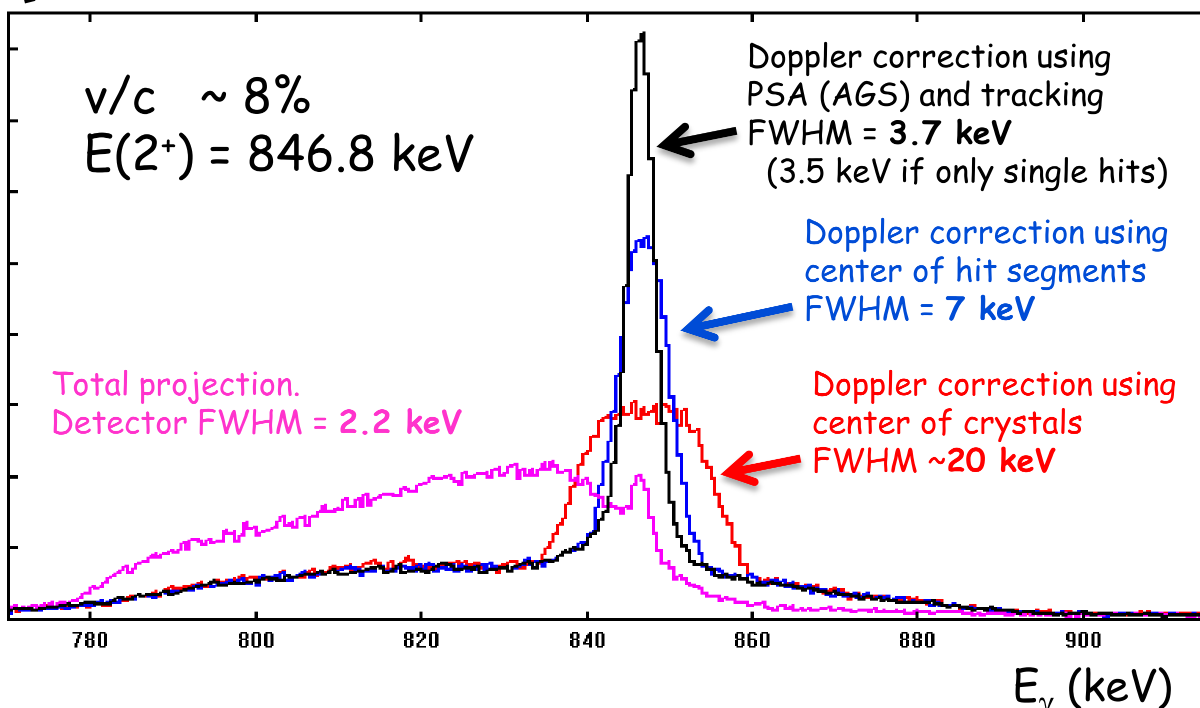
220 MeV $^{56}Fe \rightarrow {}^{197}Au$

ATC1 + DANTE





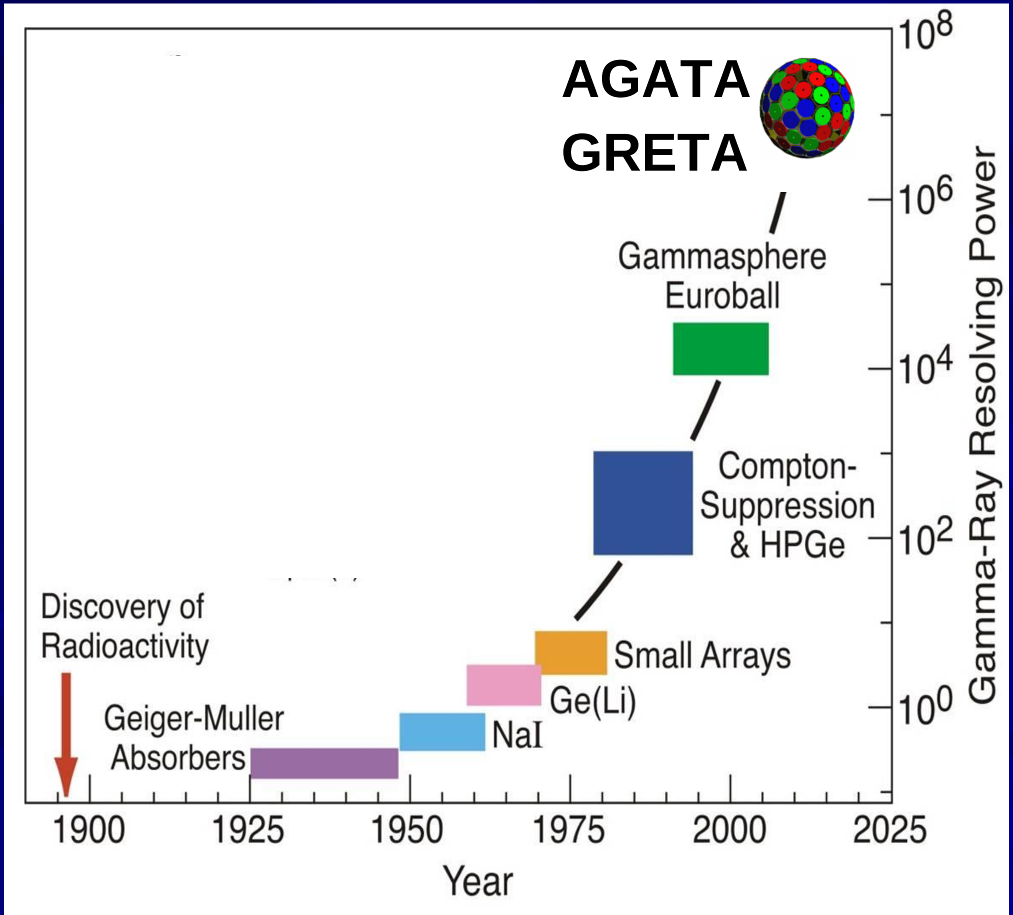




Summary

From Ge(Li) detectors to γ-ray Tracking Arrays

Gain: 7 orders of magnitude in resolving power



Position-sensitive Ge detectors:
A challenging technology

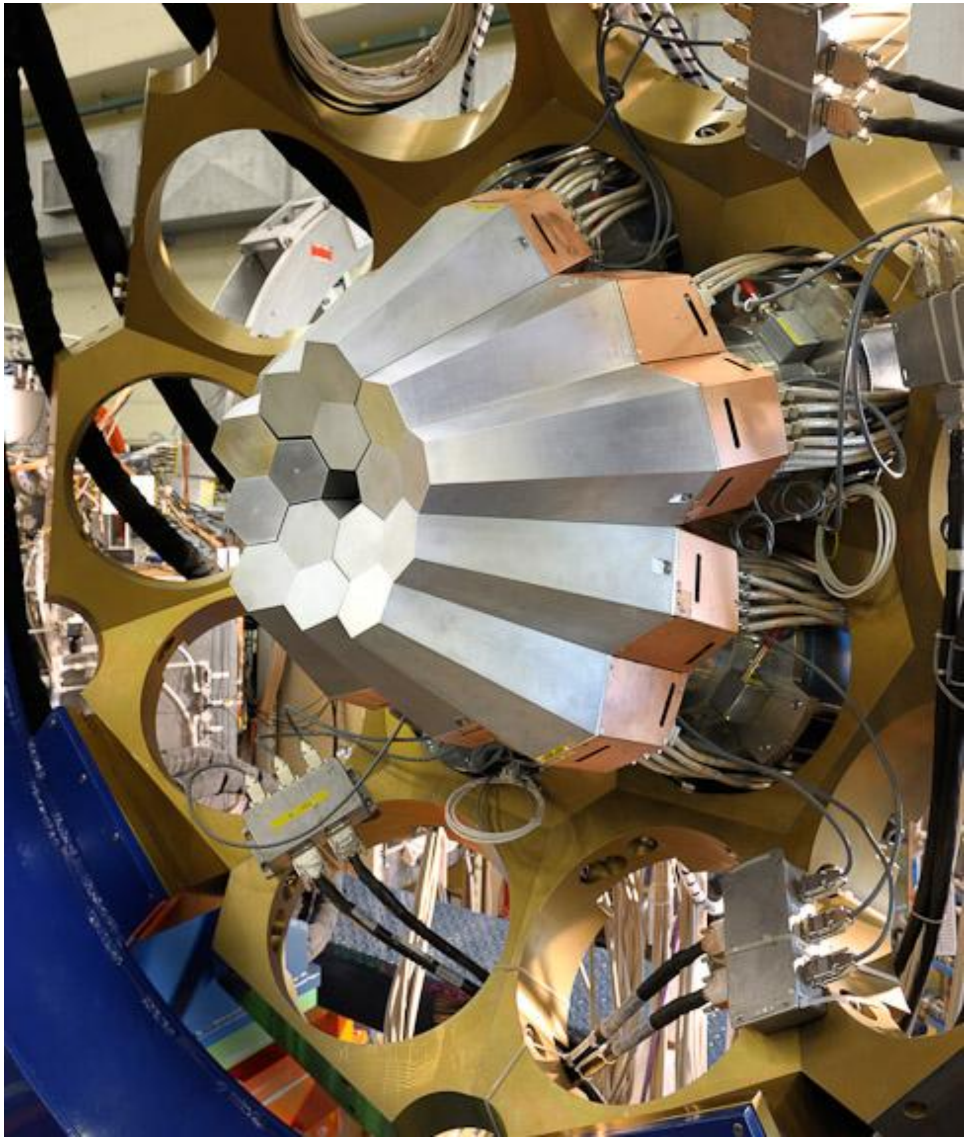
Allows for γ-ray tracking, improves energy resolution, gives a better understanding of the interactions of radiation with the detector

Almost optimal performance achieved for the AGATA triple-cluster detector

Can this technology be transferred to low-background experiments?

The AGATA collaboration:

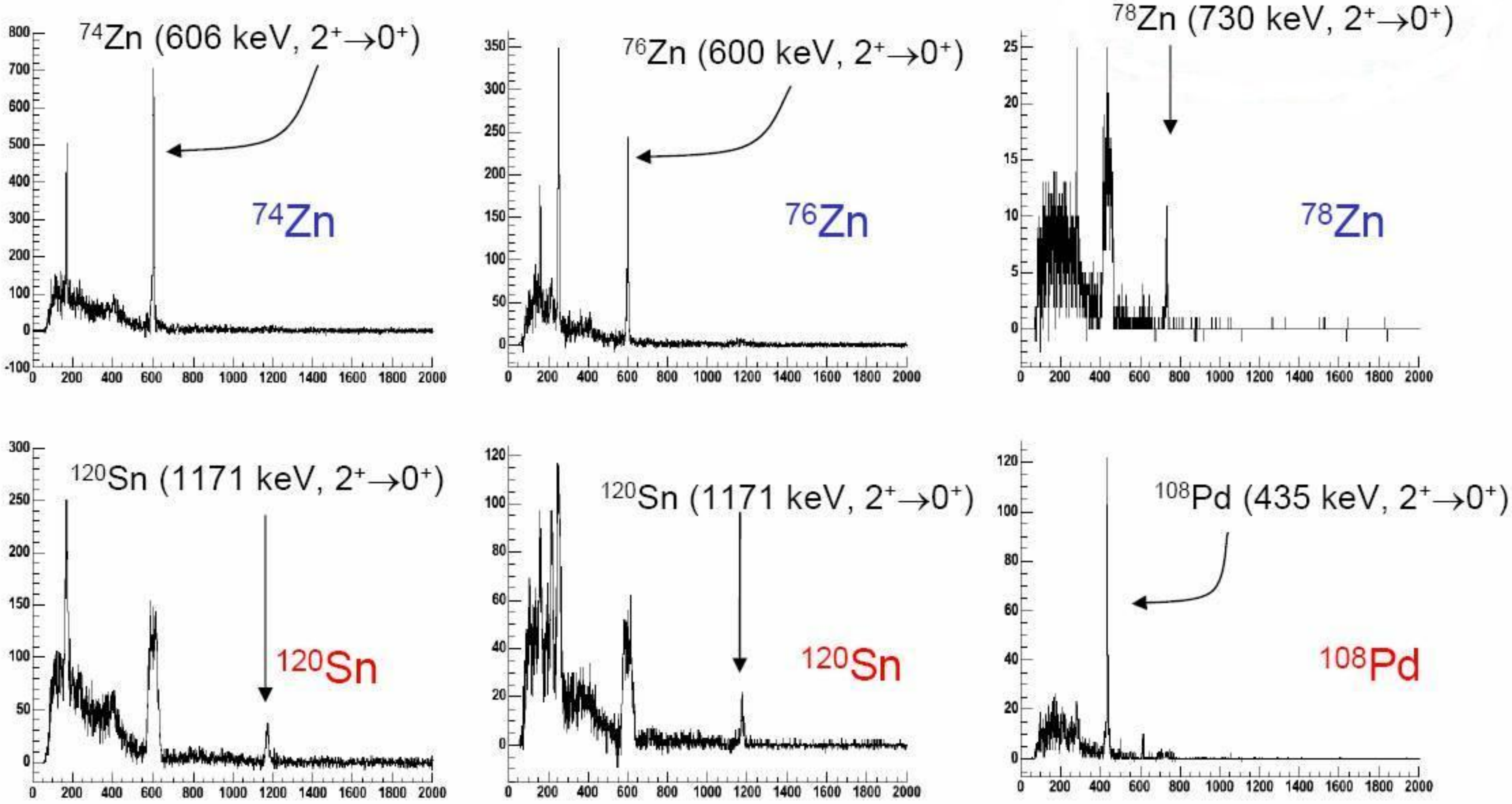
IPN Lyon, France
Univ. Lund, Sweden
Univ. Manchester, UK
INFN/Univ. Milano, Italy
TU München, Germany
INFN Napoli, Italy
CSNSM Orsay, France
IPN Orsay, France
INFN/Univ. Padova, Italy
Univ. Paisley, UK
INFN Perugia, Italy
CEA Saclay, France, Dapnia
Univ. Sofia, Bulgaria
KTH Stockholm, Sweden
IreS Strasbourg, France
Univ. Surrey, UK
IPJ Swierk, Poland
Univ. Warsaw, Poland
Univ. Uppsala, Sweden
Univ. York, UK



Univ. Ankara, Turkey
NIPNE Bucharest, Romania
Univ. Brighton, UK
GANIL, Caen, France
Univ. Camerino, Italy
NBI Copenhagen, Danmark
Univ. Cracow, Poland
CLRC Daresbury, UK
GSI Darmstadt, Germany
TU Darmstadt, Germany
INFN Firenze, Italy
INFN Genova, Italy
Univ. Göteborg, Sweden
Univ. Jyväskylä, Finland
Univ. Keele, UK
Univ. Köln, Germany
IFJ PAN Krakow, Poland
INFN Legnaro, Italy
Univ. Liverpool, UK
Univ. Istanbul, Turkey

AGATA Homepage : http://www-w2k.gsi.de/agata/

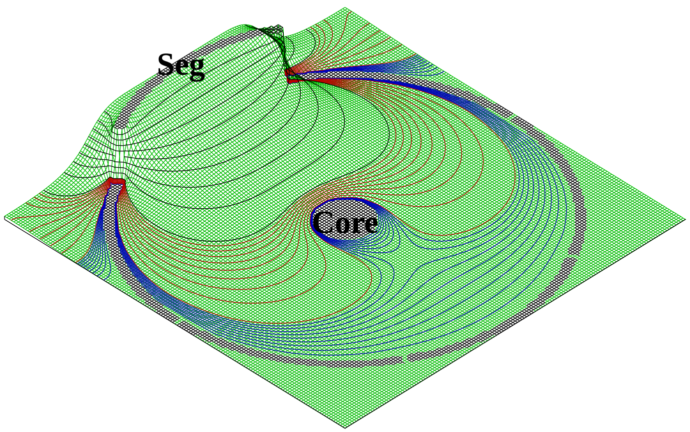
Coulomb excitation of neutron-rich Zn isotopes



J. Van der Walle et al., PRL 99 (2007) 142501

Simulating the detector response

- Weighting Fields



- Charge dynamics

  -Electron mobility

  -Hole mobility

  <u>Anisotropically</u>
  depending on the
  Field strength

  -Space charge

- Electronic Response

  -Bandwidth

  -Anti-aliasing filter

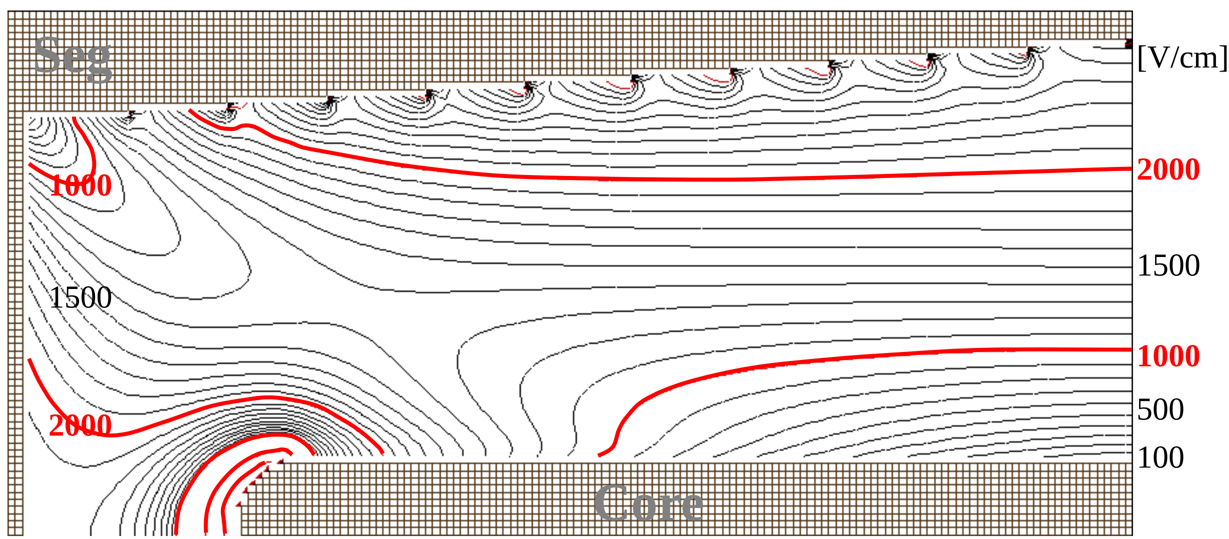
  -Data Treatment

  -Crosstalk

Shockley-Ramo theorem:

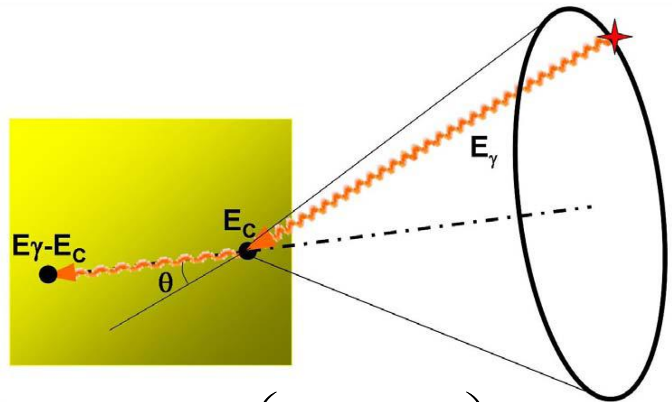
Gives charge induced at the electrode by a unit charge as function of its place in the detector

NIM A 463 (2001) 250-267

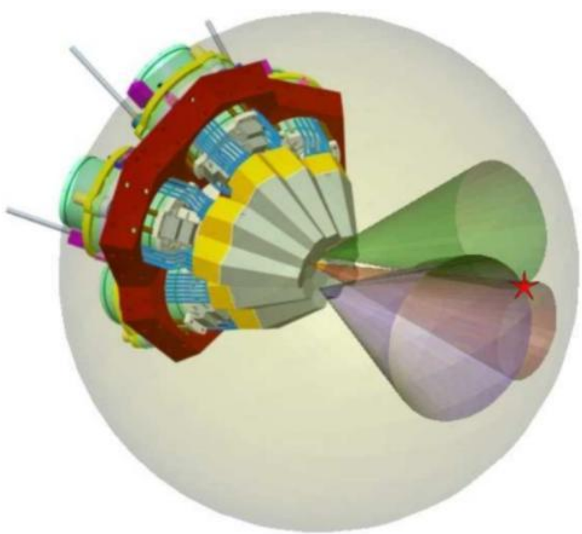


Imaging of E_γ=1332 keV gamma rays

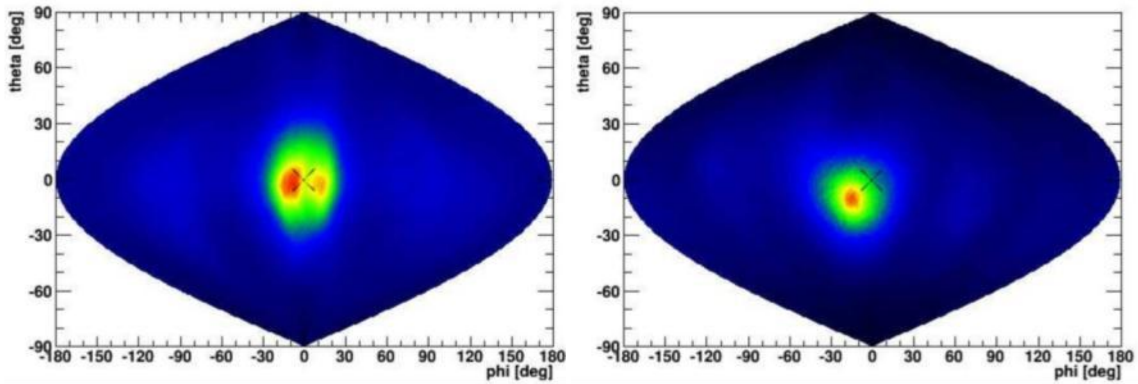
AGATA used as a big Compton Camera



$$\cos\theta = 1 + \left(\frac{1}{E_\gamma} - \frac{1}{E'_\gamma}\right) m_0 c^2$$



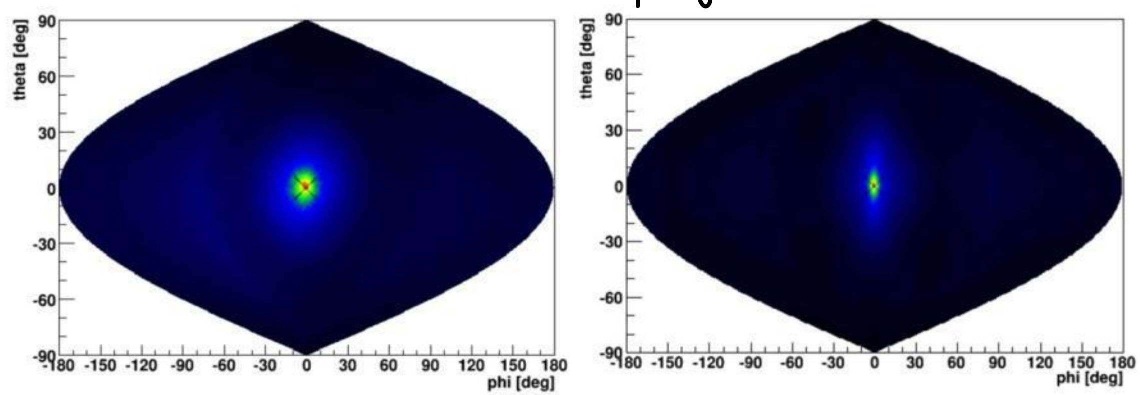
Far Field Backprojection



All 9 detectors

One detector

Near Field Backprojection



All 9 detectors

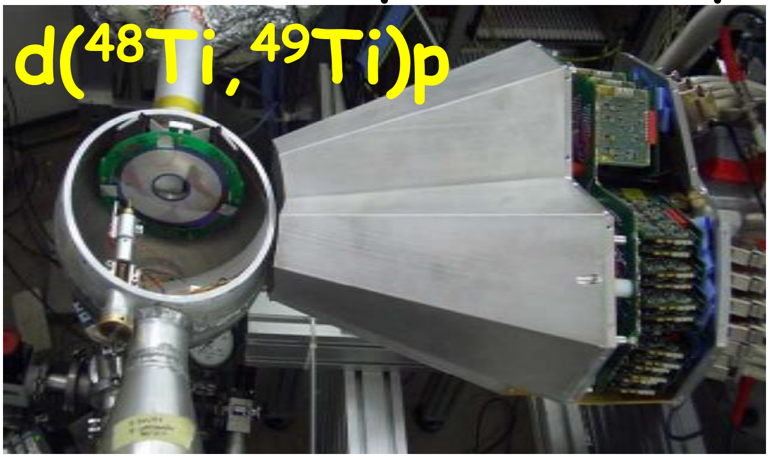
One detector

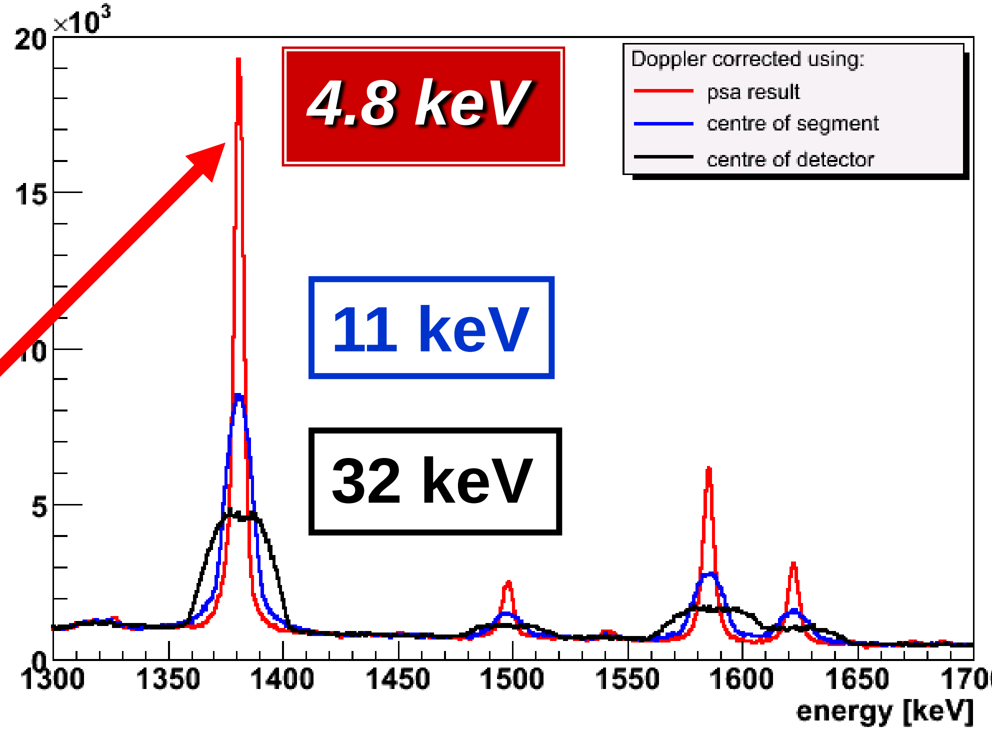
Source at 51 cm ➔ $\Delta x \sim \Delta y \sim 2$ mm $\Delta z \sim 2$ cm

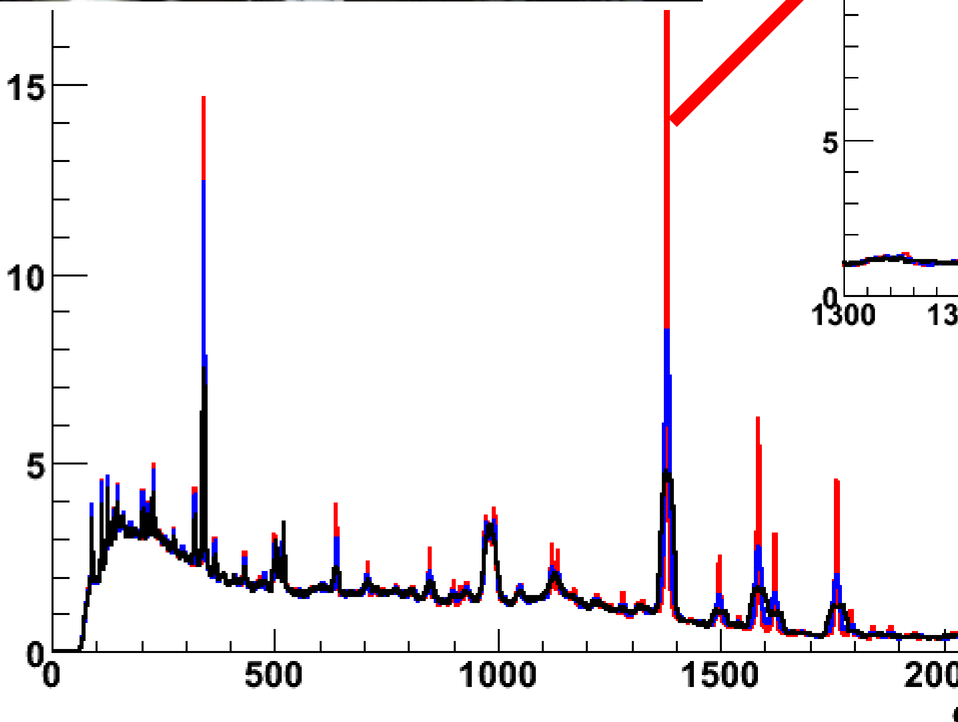
Francesco Recchia

Doppler correction using PSA results

Experiment performed at Köln in 2005







Position resolution derived by comparing with MC

➔ 4.5 mm FWHM

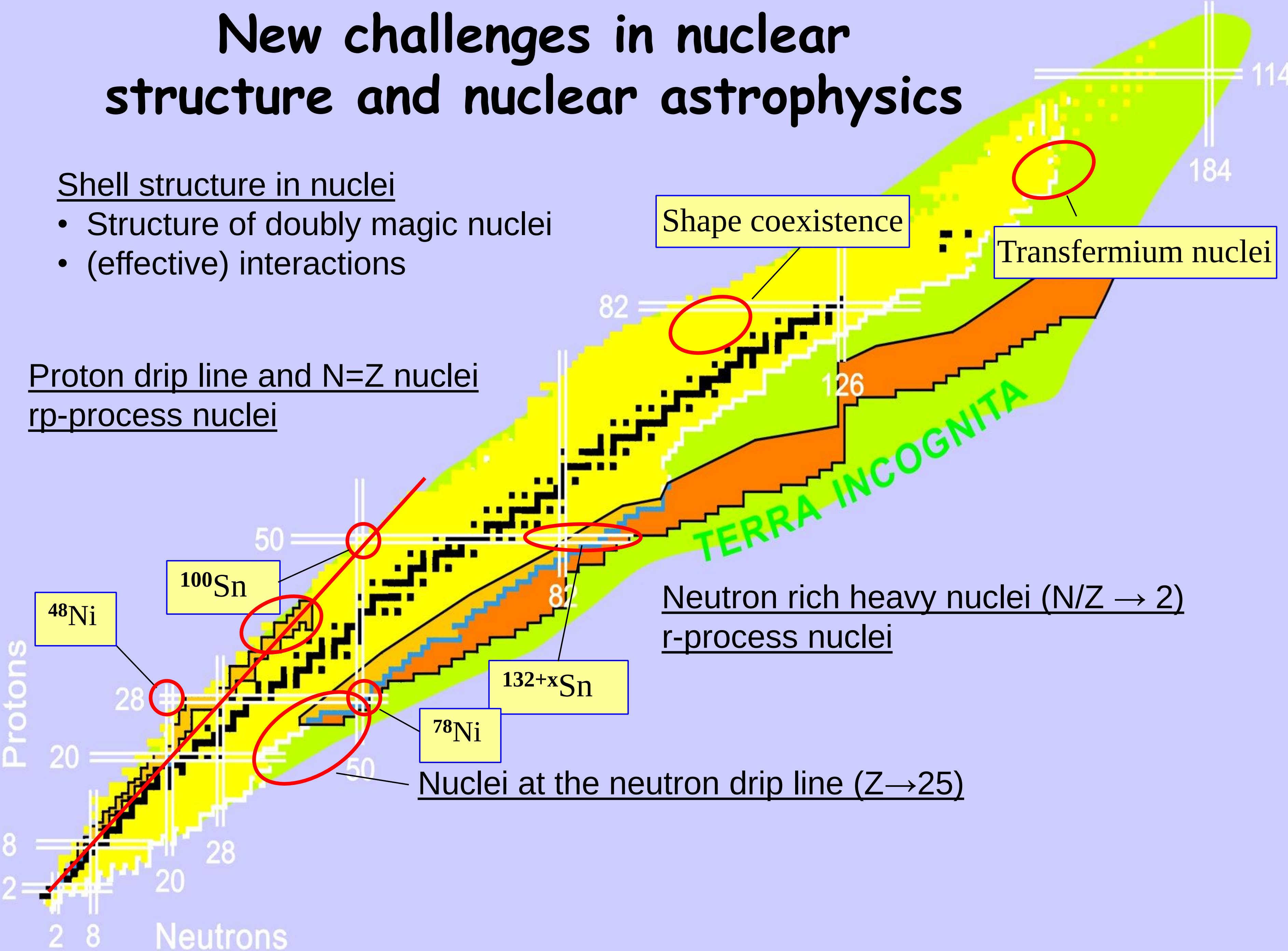
New challenges in nuclear structure and nuclear astrophysics

Shell structure in nuclei
- Structure of doubly magic nuclei
- (effective) interactions

Proton drip line and N=Z nuclei
rp-process nuclei

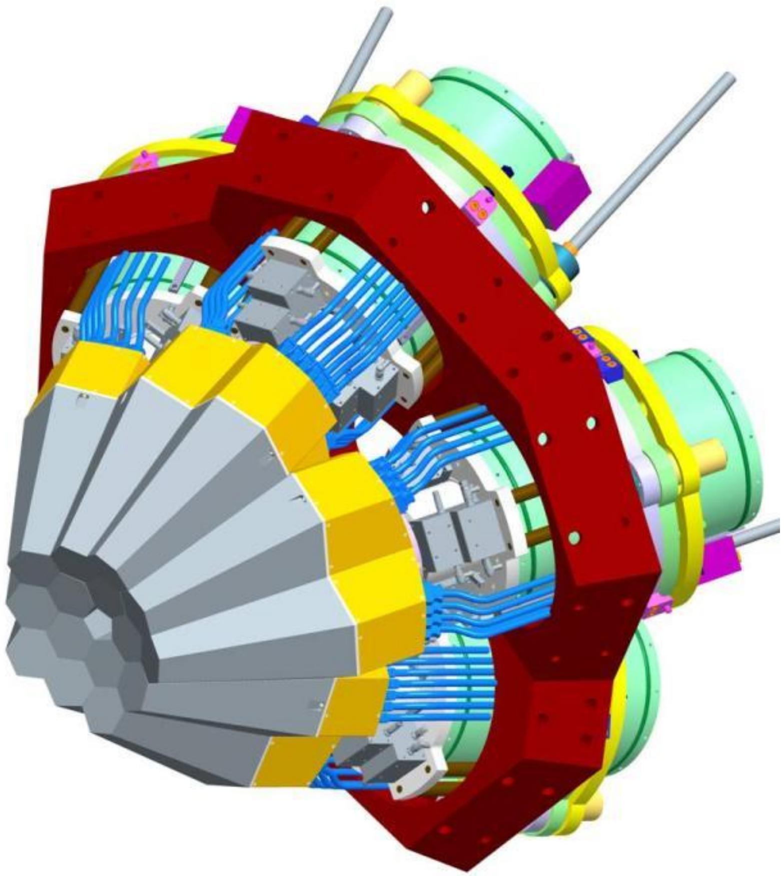
Neutron rich heavy nuclei (N/Z → 2)
r-process nuclei

Nuclei at the neutron drip line (Z→25)



The AGATA Demonstrator

Objective of the R&D phase 2003-2009



5 asymmetric triple-clusters

15 36-fold segmented crystals
540 segments
555 high-resolution digital-channels

Eff. 3 – 8 % @ M_{γ} = 1
Eff. 2 – 4 % @ M_{γ} = 30

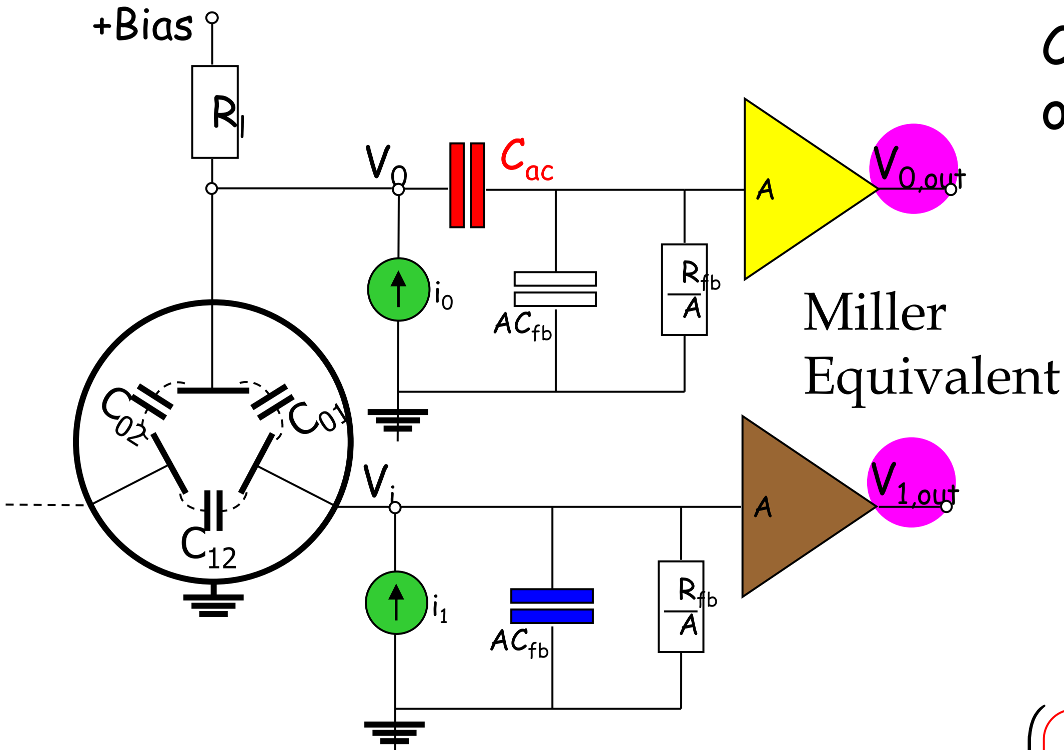
Real time operation

Pulse Shape Analysis
γ-ray Tracking

Hosting sites

LNL → 2009-2011
GSI → 2012
GANIL → 2014

A model to describe cross talk



Cross talk is intrinsic property of segmented detectors !

Segment-to-Core

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

Proportional cross talk - Energy

Derivative cross talk – PSA

Core-to-Seg

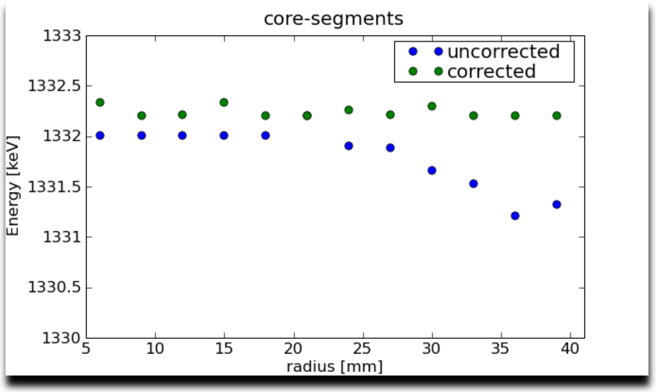
~ 1pF/1000pF

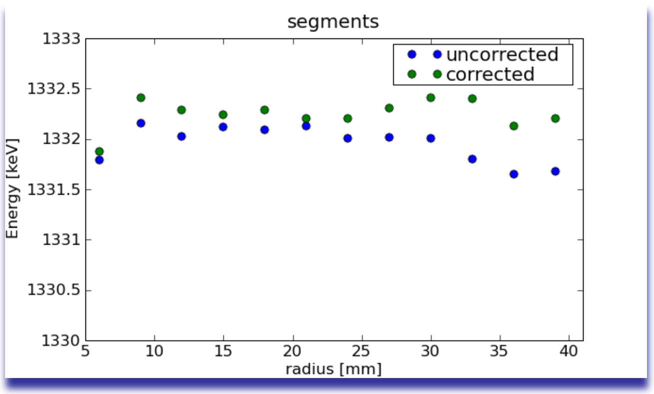
Segment-to-Segment

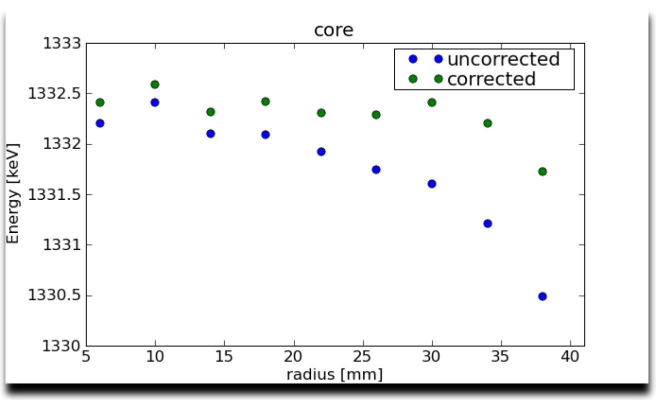
~1pF/(10000 · 1pF)

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

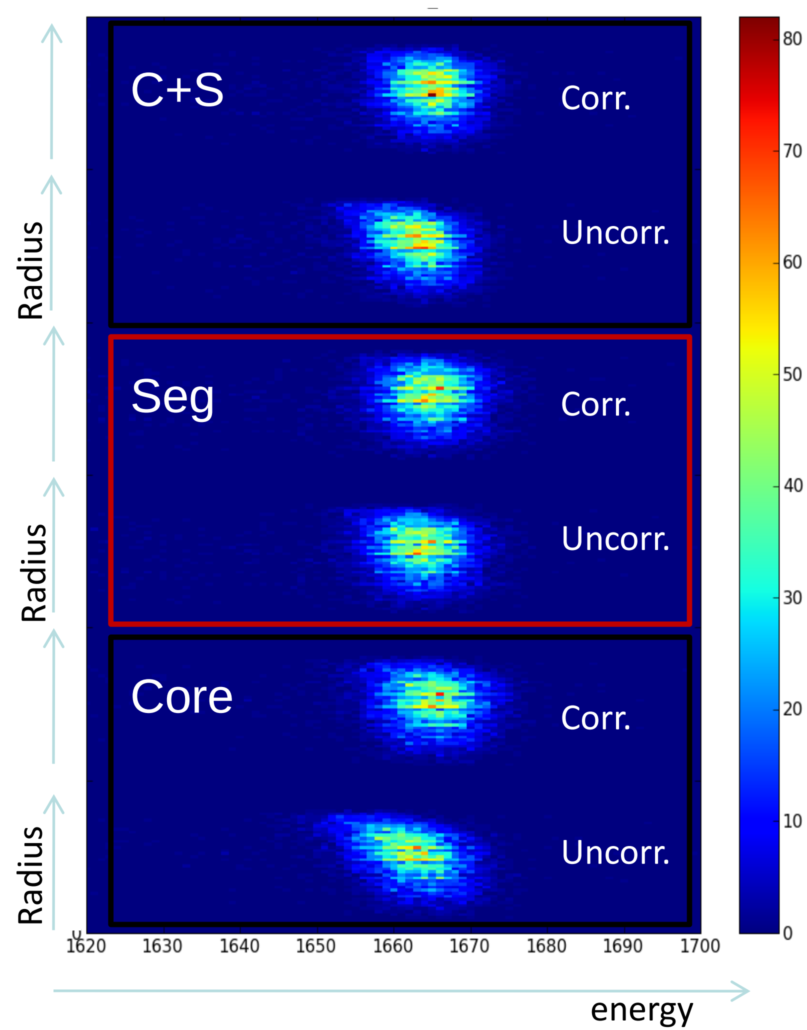
Coaxial part of detector







Electron trapping present in any n-type detector



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