Nuclear Structure studies using high-resolution techniques

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- Why high resolution and how
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    - → Performance, back-ground reduction and selectivity
    - → Angular correlations, polarization and lifetimes
- Advanced γ-ray tracking
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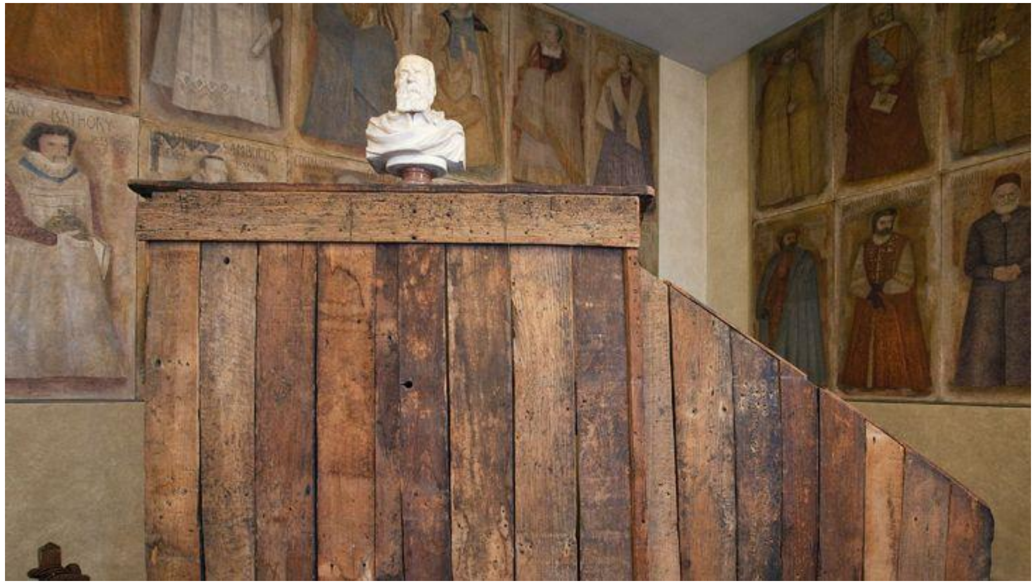
  - → The AGATA project

(Main) bibliography of today's lecture

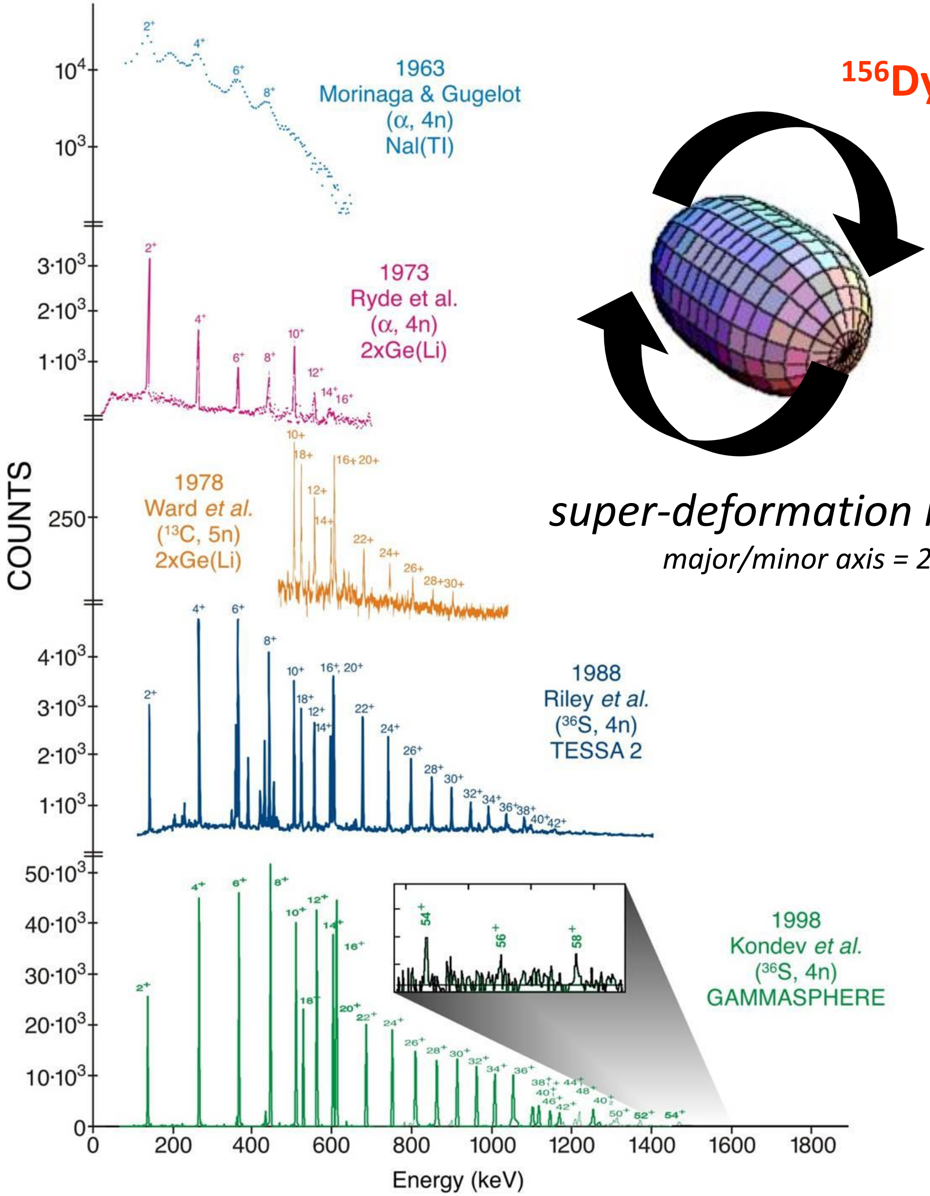
G.F. Knoll "Radiation Detection and Measurement"

F. Recchia and C. Michelagnoli, in Lec. Notes in Phys. (Euroschool Vol. VI)

C. Michelagnoli, PhD Thesis, Univ. of Padova (2013) (and refs therein ☺)



Advances in γ-ray spectroscopy

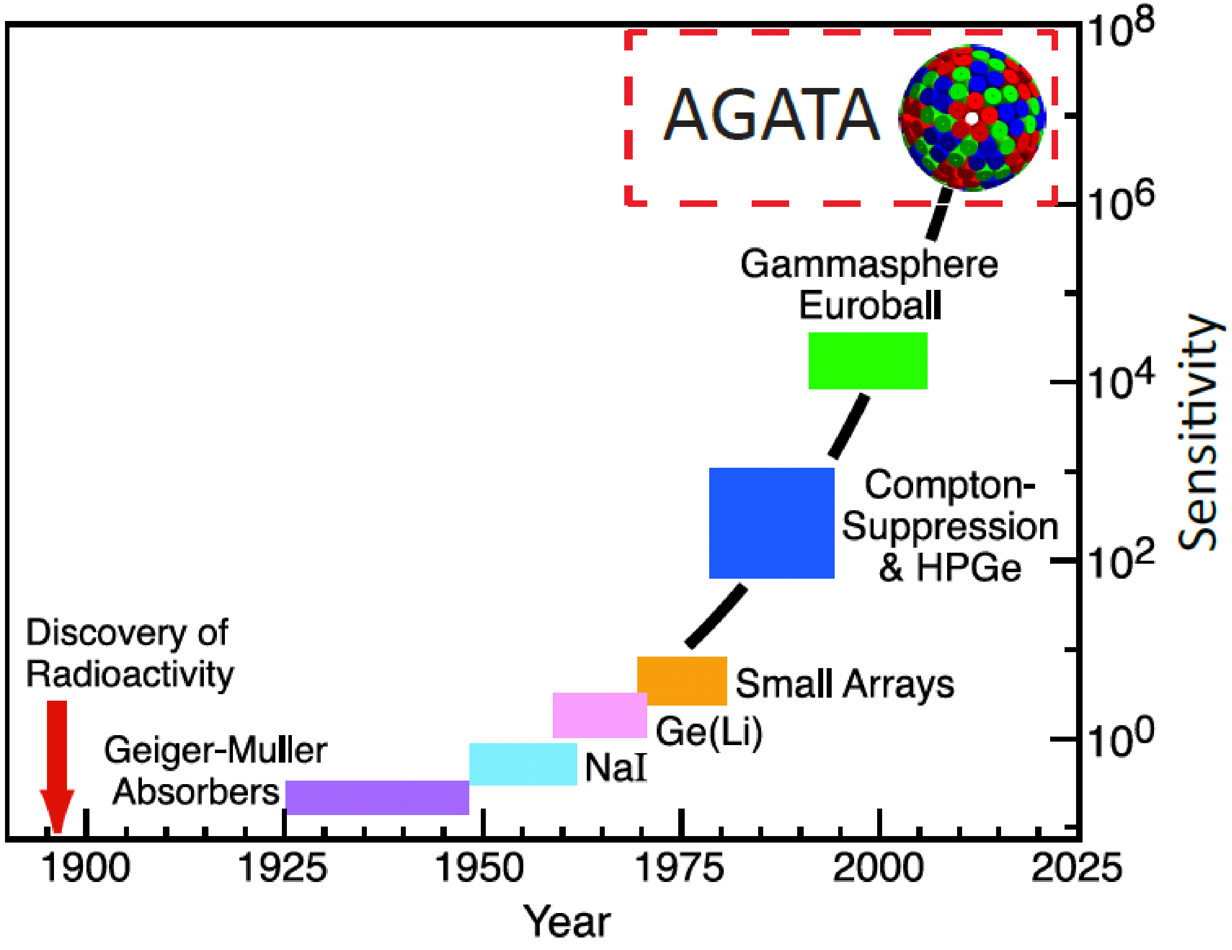


^{156}Dy

super-deformation in ^{156}D

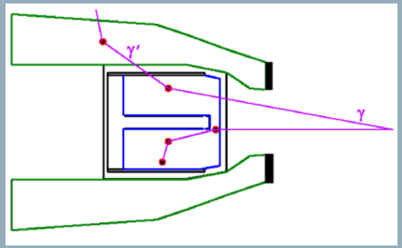
major/minor axis = 2:1

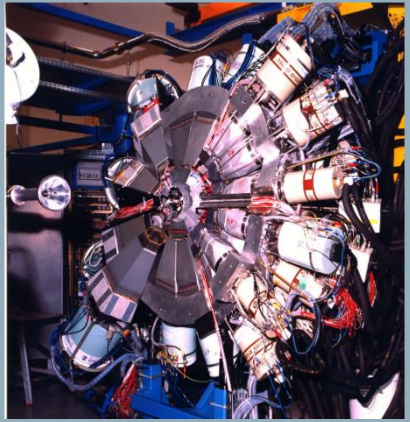
Sensitivity = inverse of the weakest channel reaction cross-section that can be measured over total cross-section



New generation HPGe arrays

Gamma Arrays based on Compton Suppressed Spectrometers



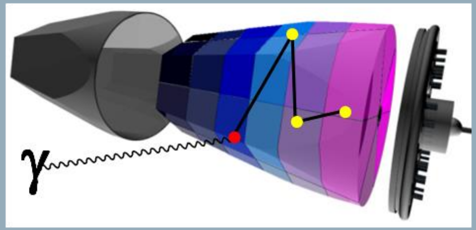


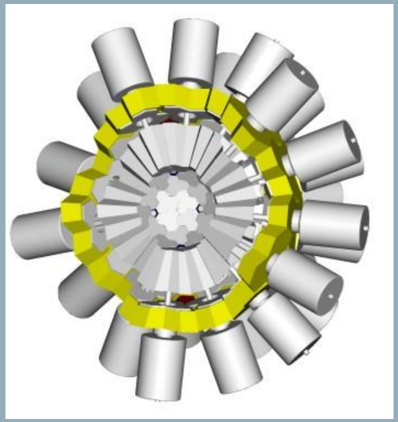
EUROBALL

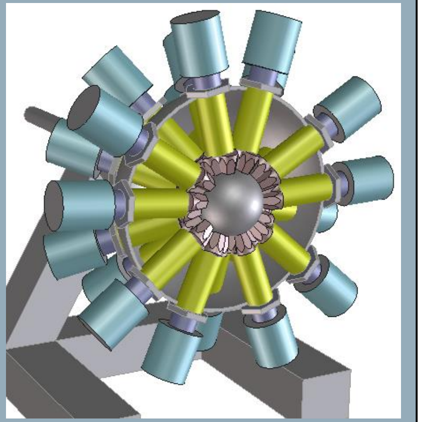
GAMMASPHERE

$\varepsilon \sim 10 — 5\ \%$
(M_γ=1 — M_γ=30)

Tracking Arrays based on Position Sensitive Ge Detectors







AGATA

GRETA

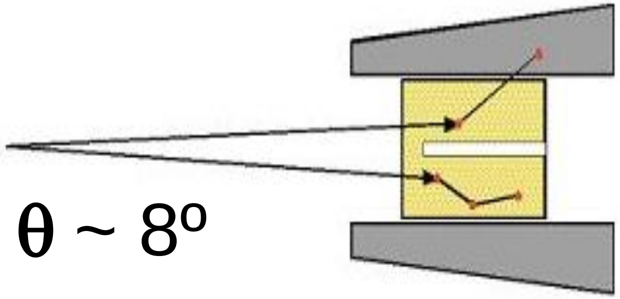
$\varepsilon \sim 50 — 25\ \%$
(M_γ=1 — M_γ=30)

NEUTRONS FOR SOCIETY

From conventional Ge to γ-ray tracking

Compton-shielded Ge

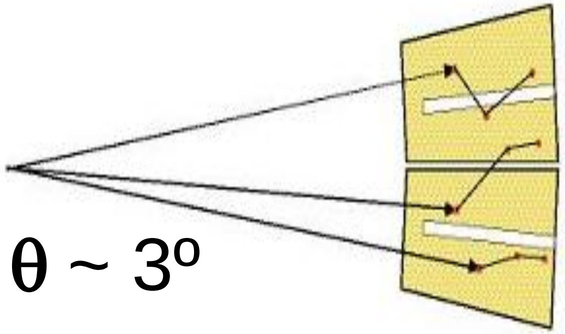
ε_{ph} ~ 10%
N_{det} ~ 100
Ω ~40%



Efficiency is lost due to the solid angle covered by the shield; poor energy resolution at high recoil velocity because of the large opening angle

Ge sphere

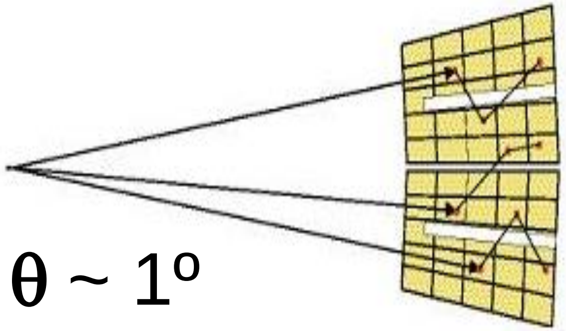
ε_{ph} ~ 50%
N_{det} ~ 1000



Using only conventional Ge detectors, too many detectors are needed to avoid summing effects and keep the resolution to good values

Ge tracking array

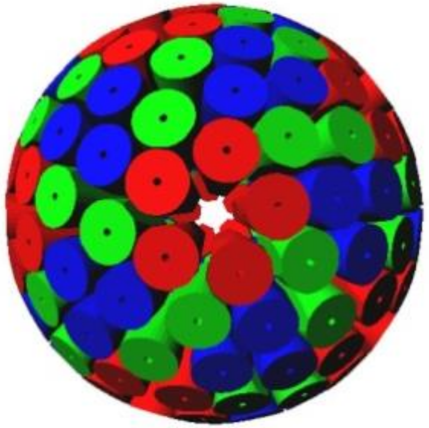
ε_{ph} ~ 50%
N_{det} ~ 100
Ω ~80%



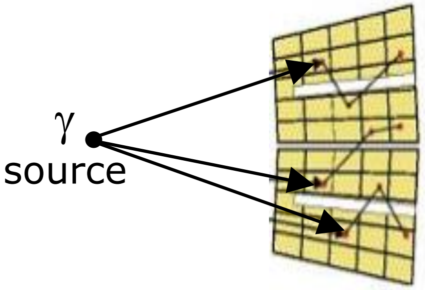
Use detectors in a non-conventional way ☺

The γ spectroscopy dream

Cover the whole detection solid angle by germanium and track the path of the γ rays inside the detector medium



- segmented detectors
- digital electronics
- timestamping of events
- analysis of pulse shapes
- tracking of γ rays



4 time more efficient than standard arrays, also for high γ multiplicity (28 % M_γ=30)

High count rate capabilities (100s KHz)

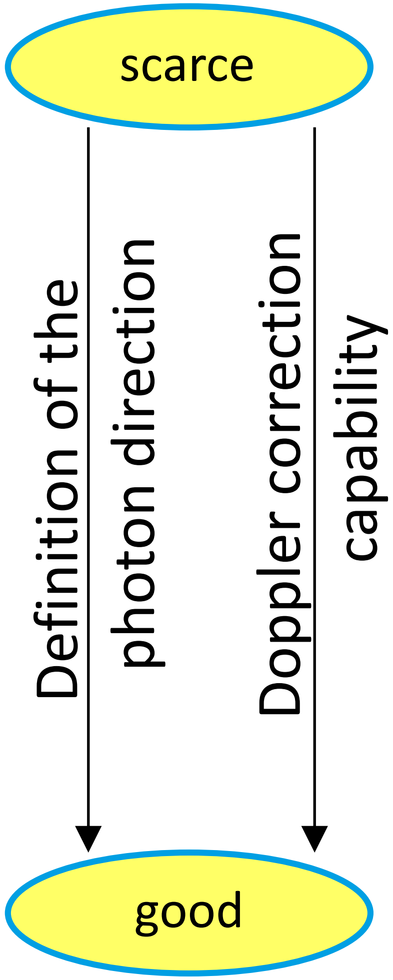
→ Study of nuclei in extreme conditions of angular momentum and neutron/proton asymmetry

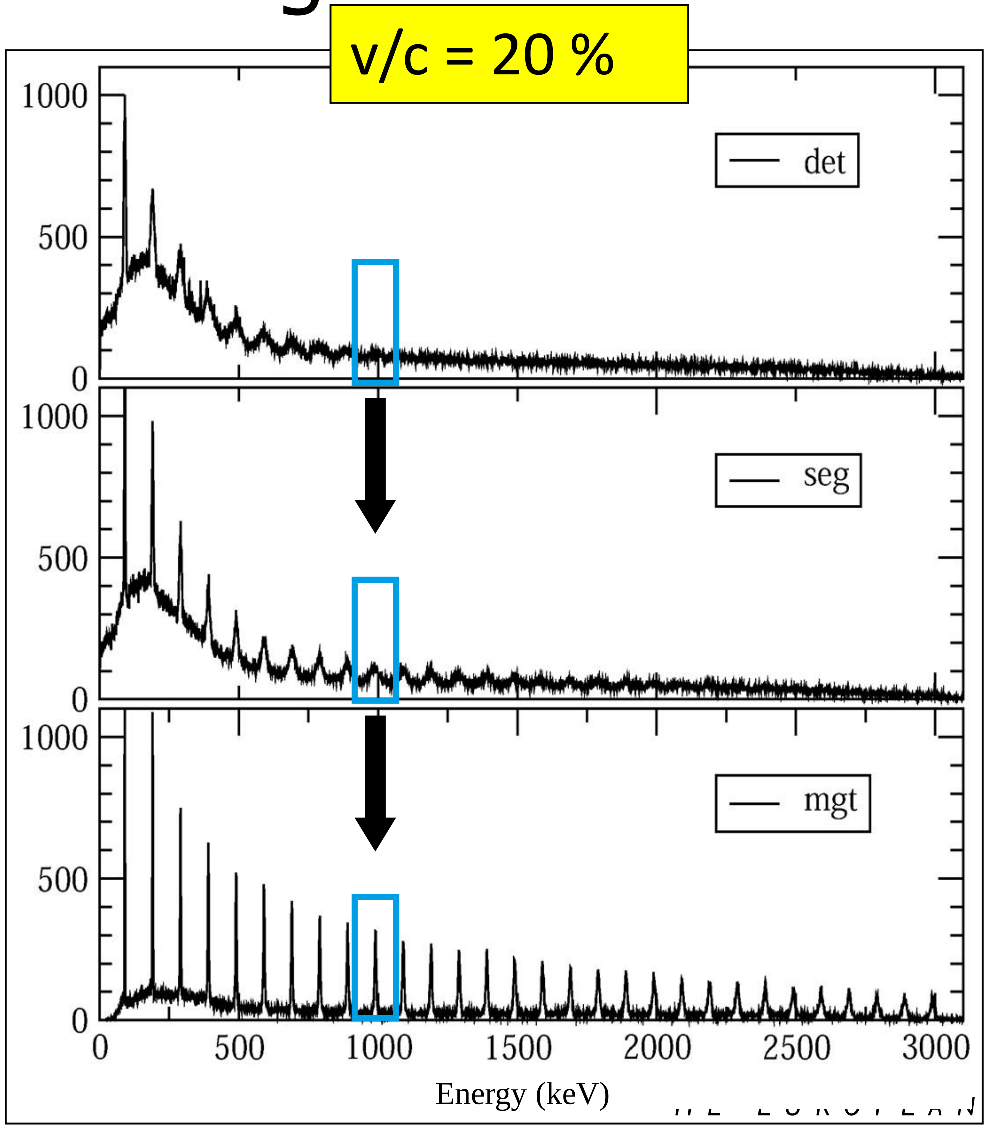
"continuous" angular distributions of the γ interaction points (θ~1°)

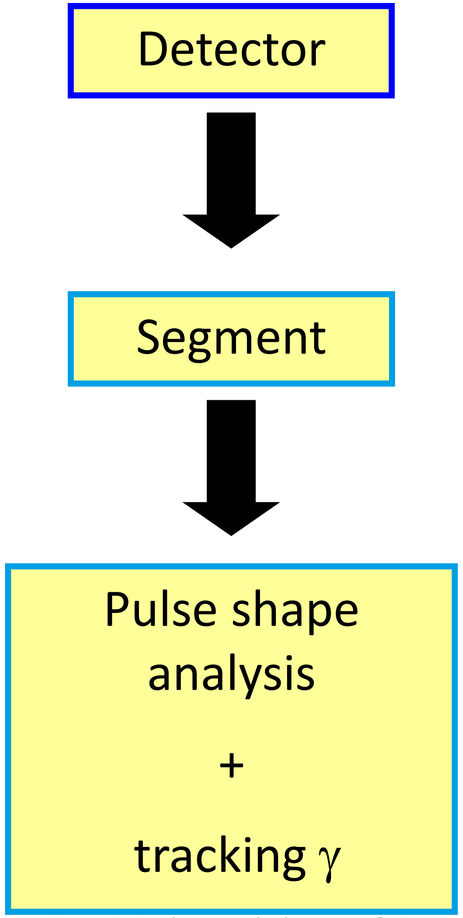
→ "perfect" Doppler correction (6 keV @ 1 MeV, β=50%)
new accuracy and sensitivity for nuclear level lifetimes
γ linear polarization

NEUTRONS FOR SOCIETY

Position resolution used to limit Doppler broadening of gammas emitted in flight

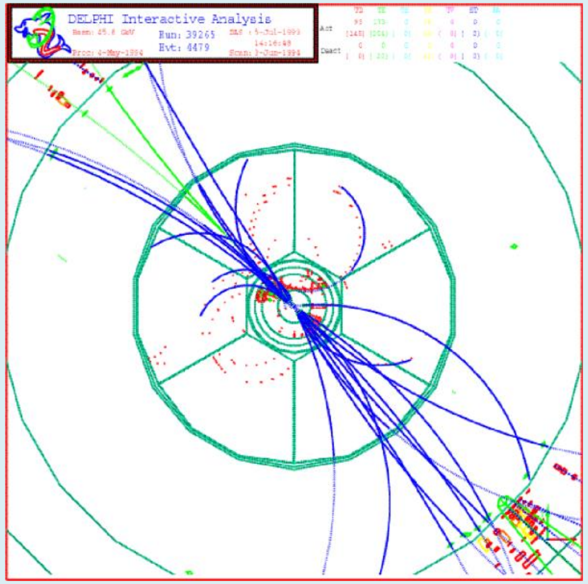






Tracking of radiation

in High Energy Physics

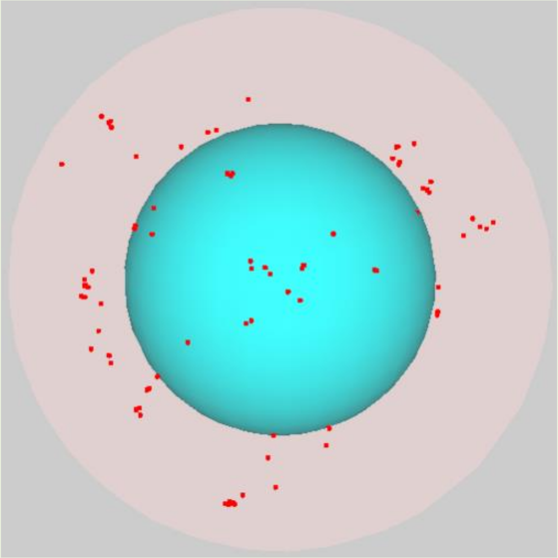


“continuous tracks” from very energetic particles

huge detectors for “one” experiment

Physics ← the study of “complete” events

in Nuclear Spectroscopy



“many” low energy (0.01 -- 10 MeV) neutral transitions with low density of energy deposition

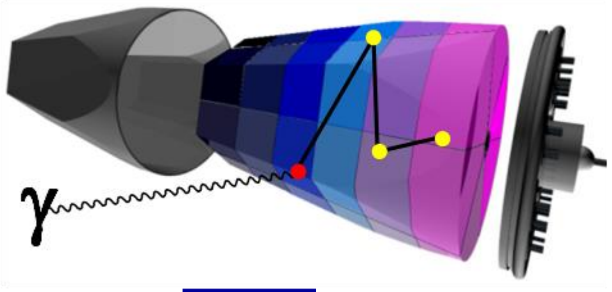
“general-purpose” detectors for a large variety of experiments

Physics ← large number of incomplete events

NEUTRONS FOR SOCIETY

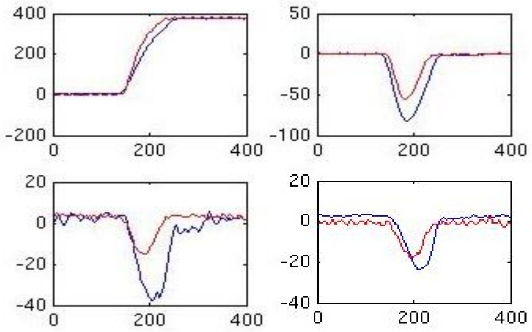
Position-sensitive operation mode and γ-ray tracking

highly segmented HPGe detectors



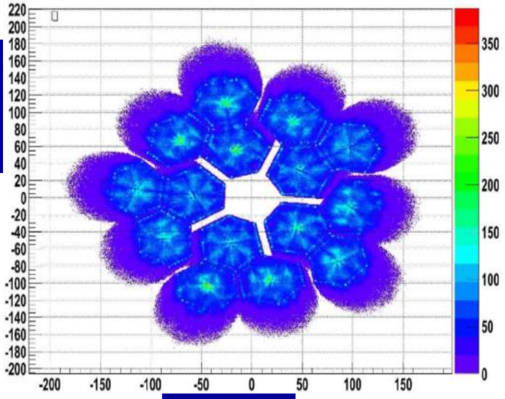
digital electronics to record sampled waveforms

Pulse Shape Analysis of the recorded waves

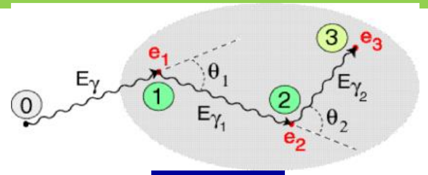


Identified interaction points (hits)

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



reconstruction of γ-rays from the hits (tracking)



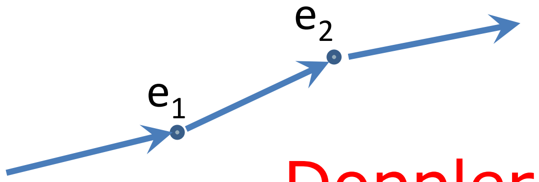
Event by event: how many gammas, for each gamma: energy, first interaction point, path

NEUTRONS FOR SOCIETY

Aim of γ-ray tracking

deposited energies and the positions
of all the interactions points
of an event in the detector

e_1, x_1, y_1, z_1
e_2, x_2, y_2, z_2
....
e_n, x_n, y_n, z_n



reconstruct individual photon trajectories
and write out photon energies,
incident and scattering directions

$E_1, (\theta,\phi)_{inc,1}, (\theta,\phi)_{sc,1}.$
...
$E_2, (\theta,\phi)_{inc,2}, (\theta,\phi)_{sc,2}.$ ...
....
$E_i, (\theta,\phi)_{inc,i}, (\theta,\phi)_{sc,i}$

Doppler correction

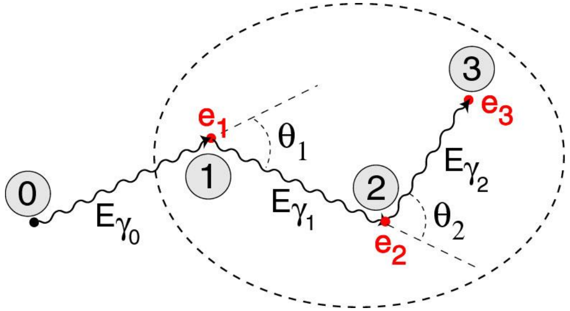
Linear polarization

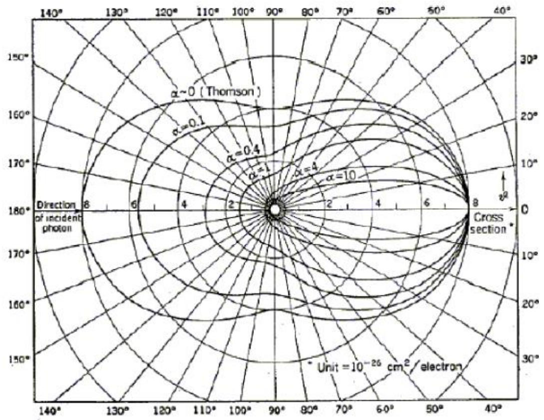
discard events corresponding to
incomplete energy release

Forward tracking implemented for AGATA

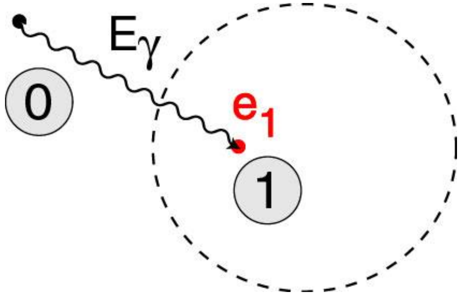
1. Create cluster pool => for each cluster, $E_{\gamma 0} = \sum$ depositions in the cluster
2. Find most probable sequence of interaction points, test the 3 mechanisms
    1. do the interaction points satisfy the **Compton** scattering rules ?

$$\chi^2 \approx \sum_{n=1}^{N-1} W_n \cdot \left(\frac{E_{\gamma'} - E_{\gamma'}^{Pos}}{E_\gamma} \right)_n^2$$



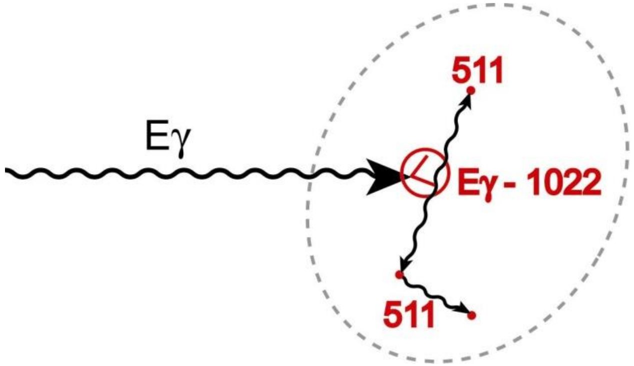


    1. does the interaction satisfy **photoelectric** conditions (e_1,depth,distance to other points) ?



    1. do the interaction points correspond to a **pair production** event ?

$$E_{1st} = E_\gamma - 2\, m_e c^2$$



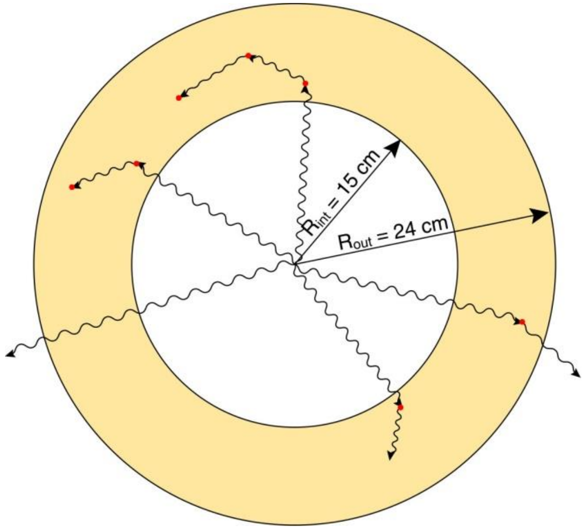
3. Select clusters based on χ^2

D.Bazzacco, Padova - A. Lopez-Martens, Orsay [NIMA 533 (2004) 454]

NEUTRONS FOR SOCIETY

Performance of the Ge shell

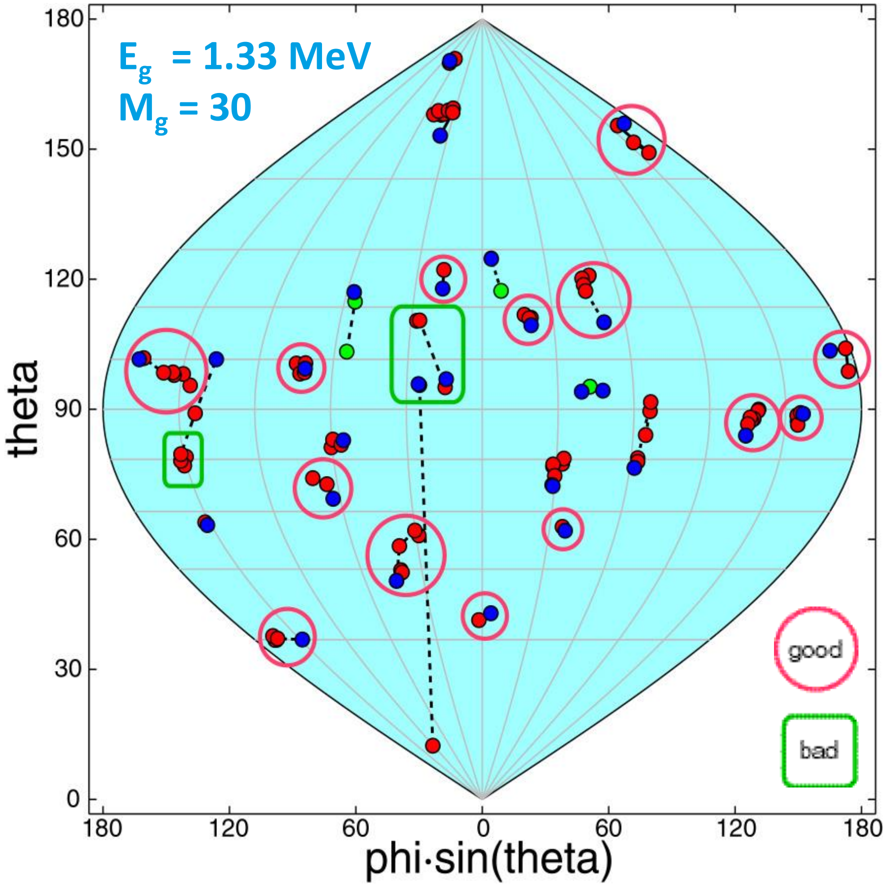
Idealized configuration to determine maximum attainable performance.



1.33 MeV	$M_\gamma = 1$	$M_\gamma = 30$
ε_{ph} (%)	65	36
P/T(%)	85	60

Reconstruction by Cluster-Tracking
Packing Distance: 5 mm
Position Resolution: 5 mm (at 100 keV)

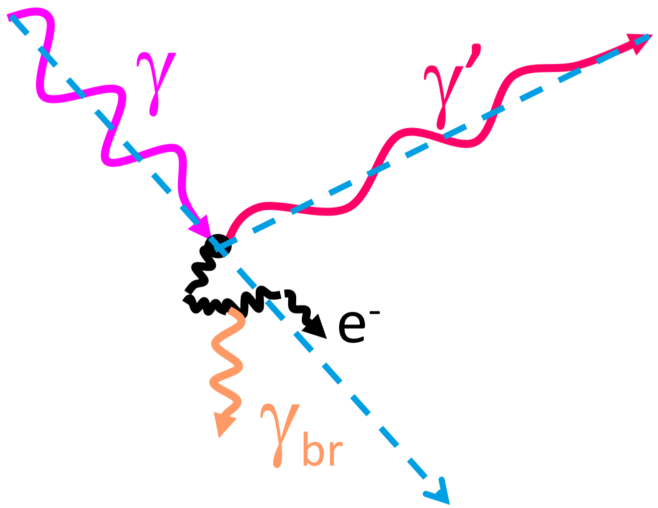
A high multiplicity event



27 gammas detected -- 23 in photopeak
16 reconstructed. -- 14 in photopeak

Fundamental Effects limiting the performance

- Interaction position $\neq$ position of energy deposition
- Bremsstrahlung

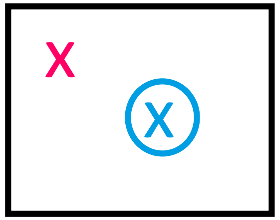


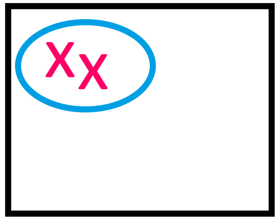
- Rayleigh scattering ➔ change incident direction (relevant at low energy & end of track)
- Momentum profile of electron ➔ change scattering direction (relevant at low energy & end of track)

Fortunately (?) these effects are masked by the poor position resolution of practical Ge detectors

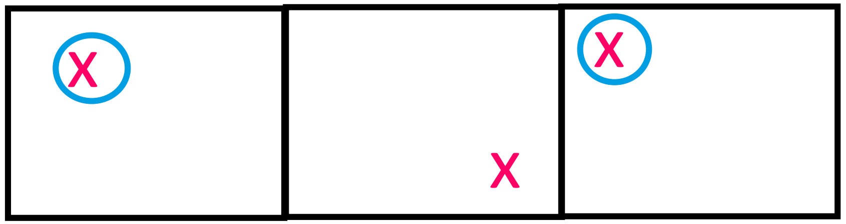
Practical Effects
limiting the performance

- uncertainty in position of interaction: (position & energy dependent)



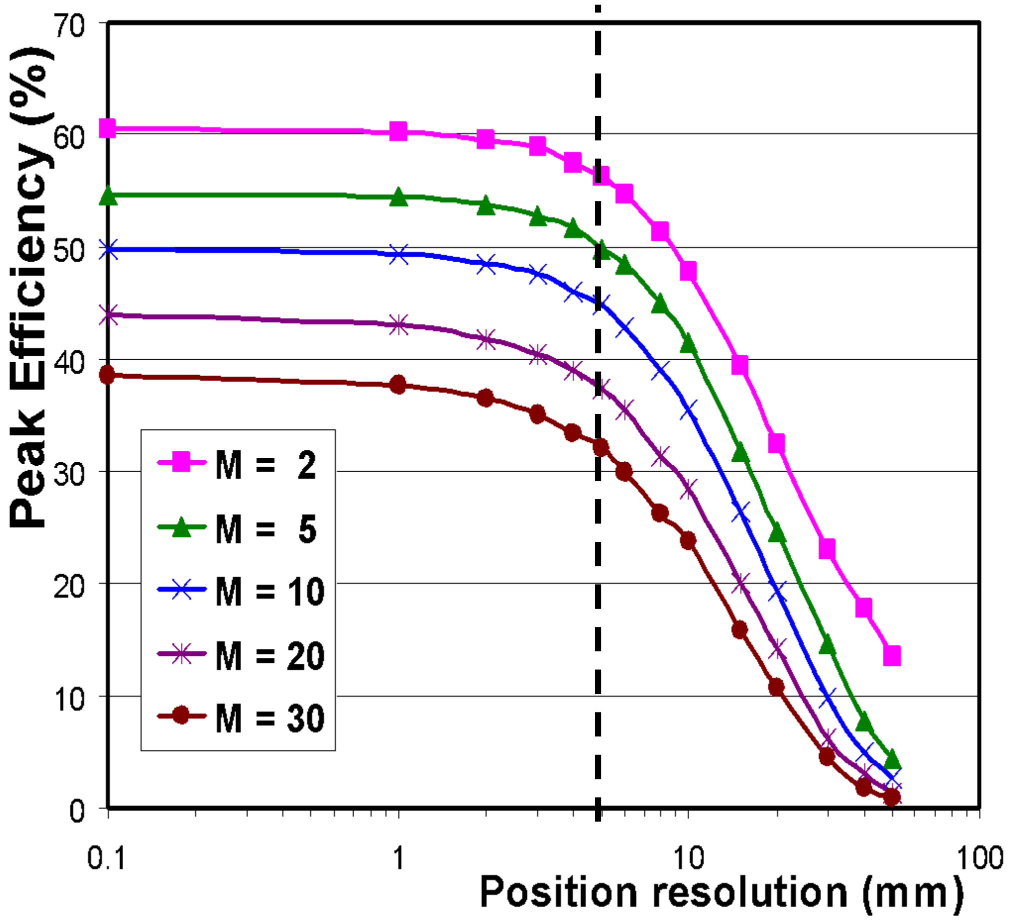


- position resolution



- energy threshold
- energy resolution
- dead materials …

Efficiency of Ge shell vs position resolution and γ multiplicity



<u>Standard shell</u>; E_γ = 1.33 MeV; Packing=Smearing; Energy independent smearing

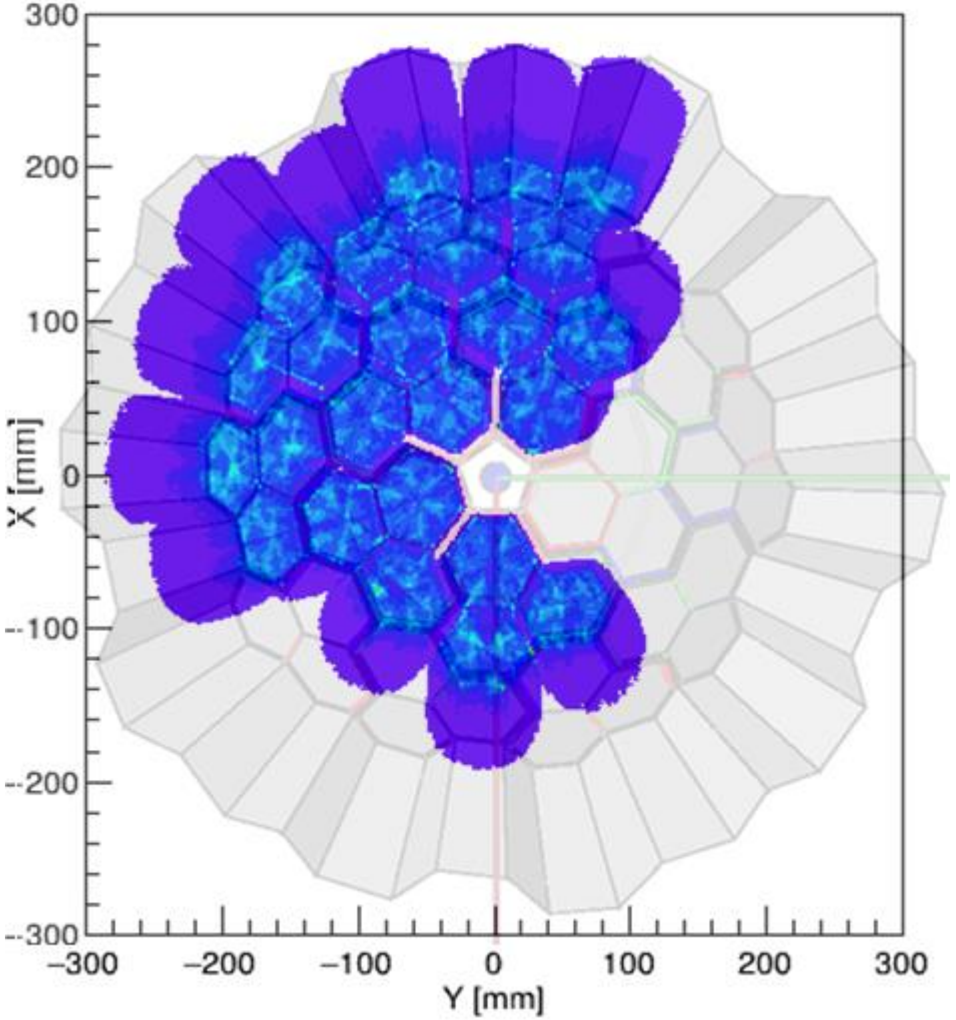
The biggest losses are due to multiplicity (mixing of points) not to bad position resolution

5 mm is the standard "<u>realistic</u>" packing and smearing assumption

If positions inside segments are not known, performance is a factor 2 worse

Sub-segment position resolution is needed

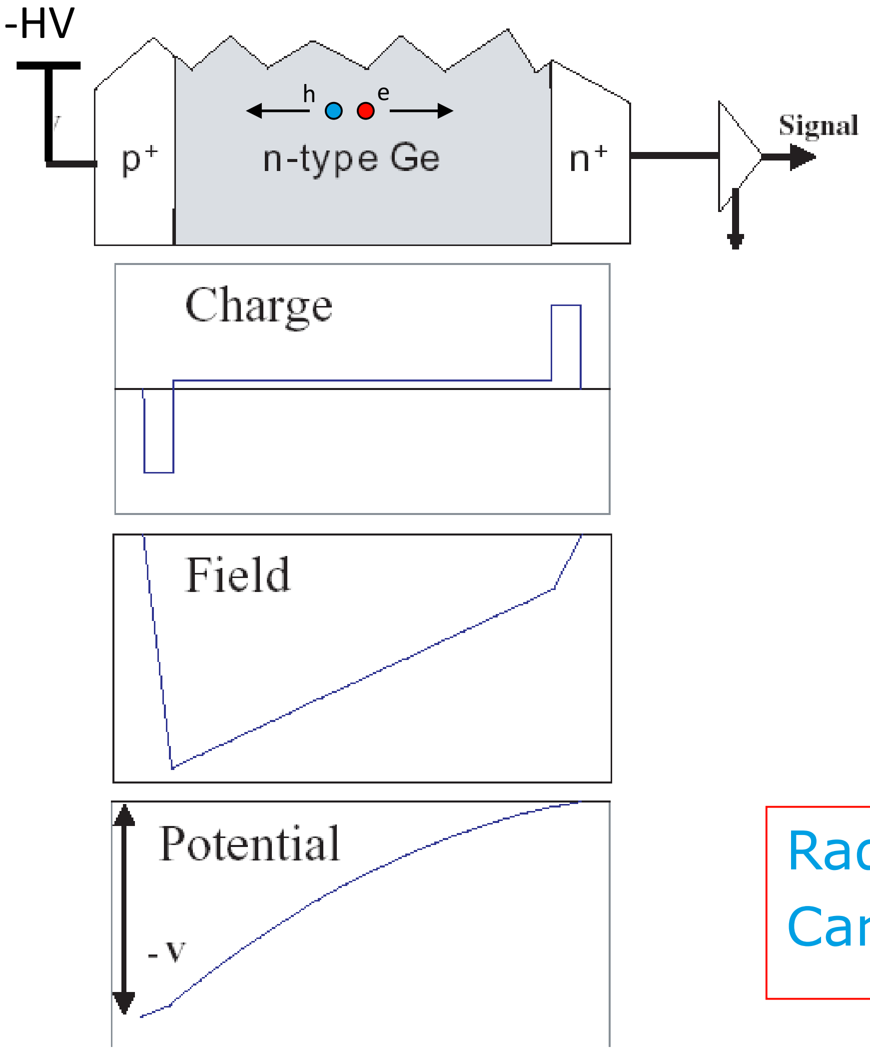
Pulse Shape Analysis (PSA)



8 AGATA Triple Clusters
(24 detectors)
@ GANIL
“captured” during an experiment

Reconstruction of the interaction points (hits)

Detector = p-i-n diode



Near intrinsic bulk (N_D~$10^{10}cm^{-3}$)

Highly doped thin contacts

N_A ~ $10^{18}cm^{-3}$ N_D ~ $10^{18}cm^{-3}$

B ~ 3 mm Li ~ 0.5 mm

Reverse bias (-HV on p^+ contact)

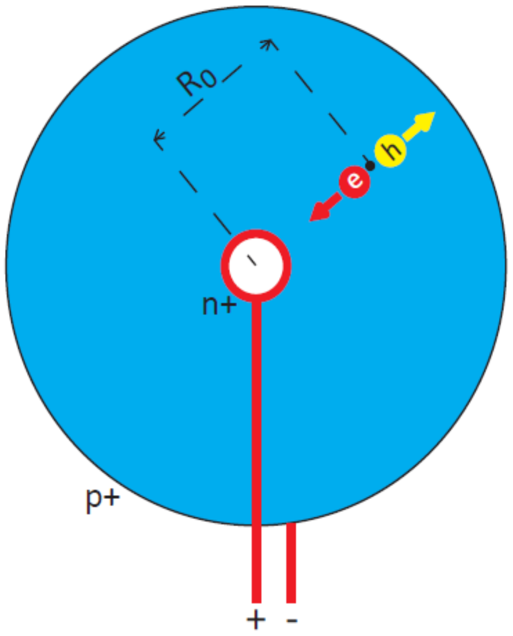
depletes bulk

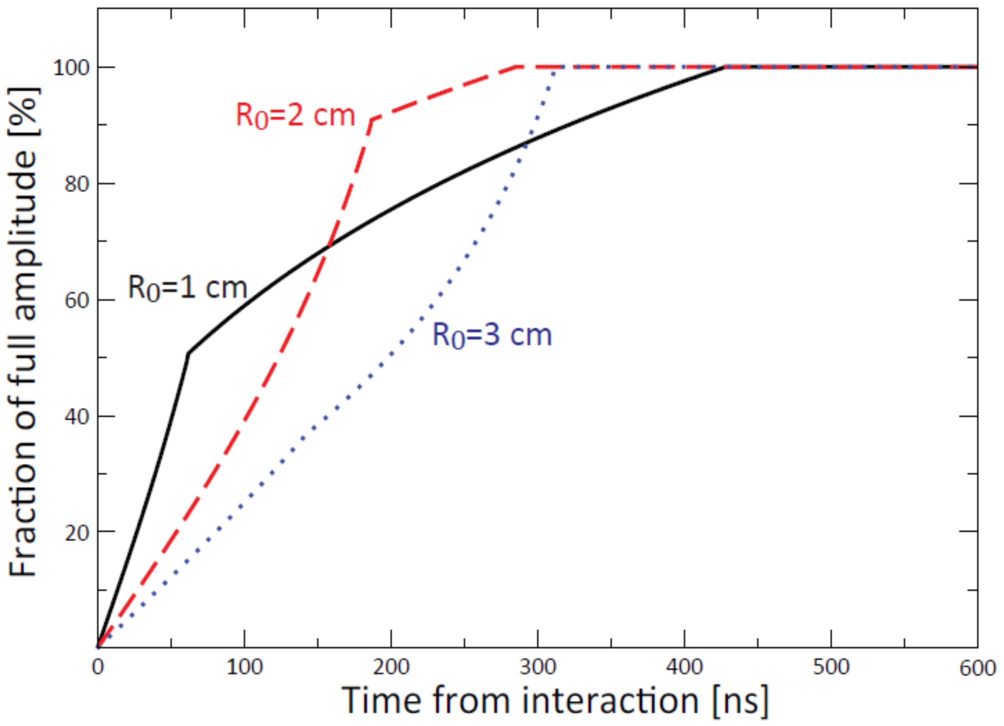
generates high electric filed

Radiation creates carriers in bulk

Carriers swept out by field → signal

Pulse shapes in a co-axial HPGe



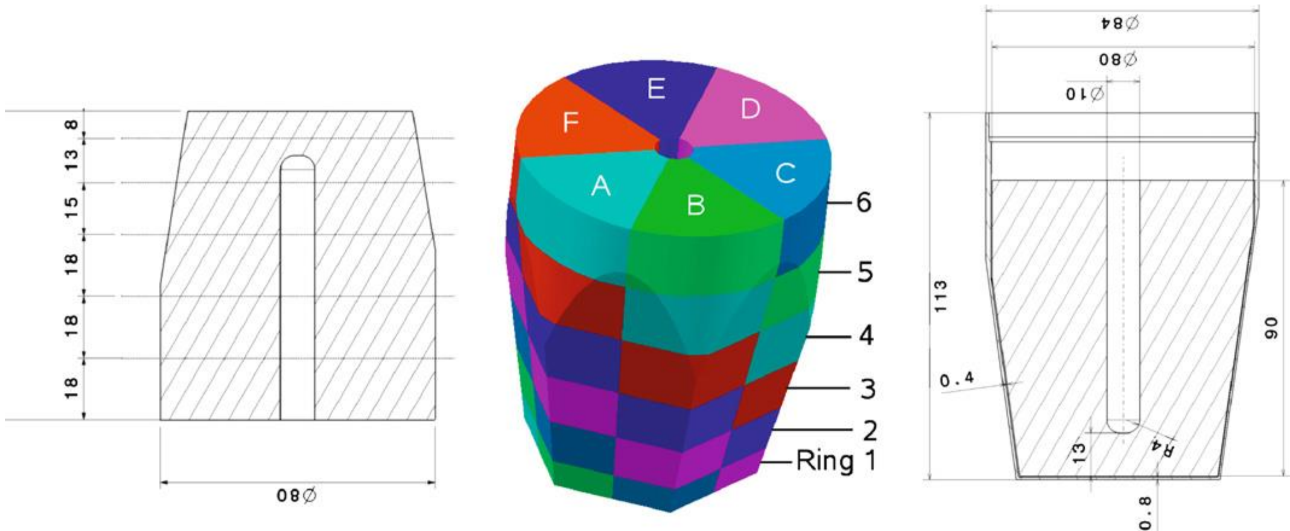


On "true" coaxial detectors, the shape depends on initial radius

Segmented detectors

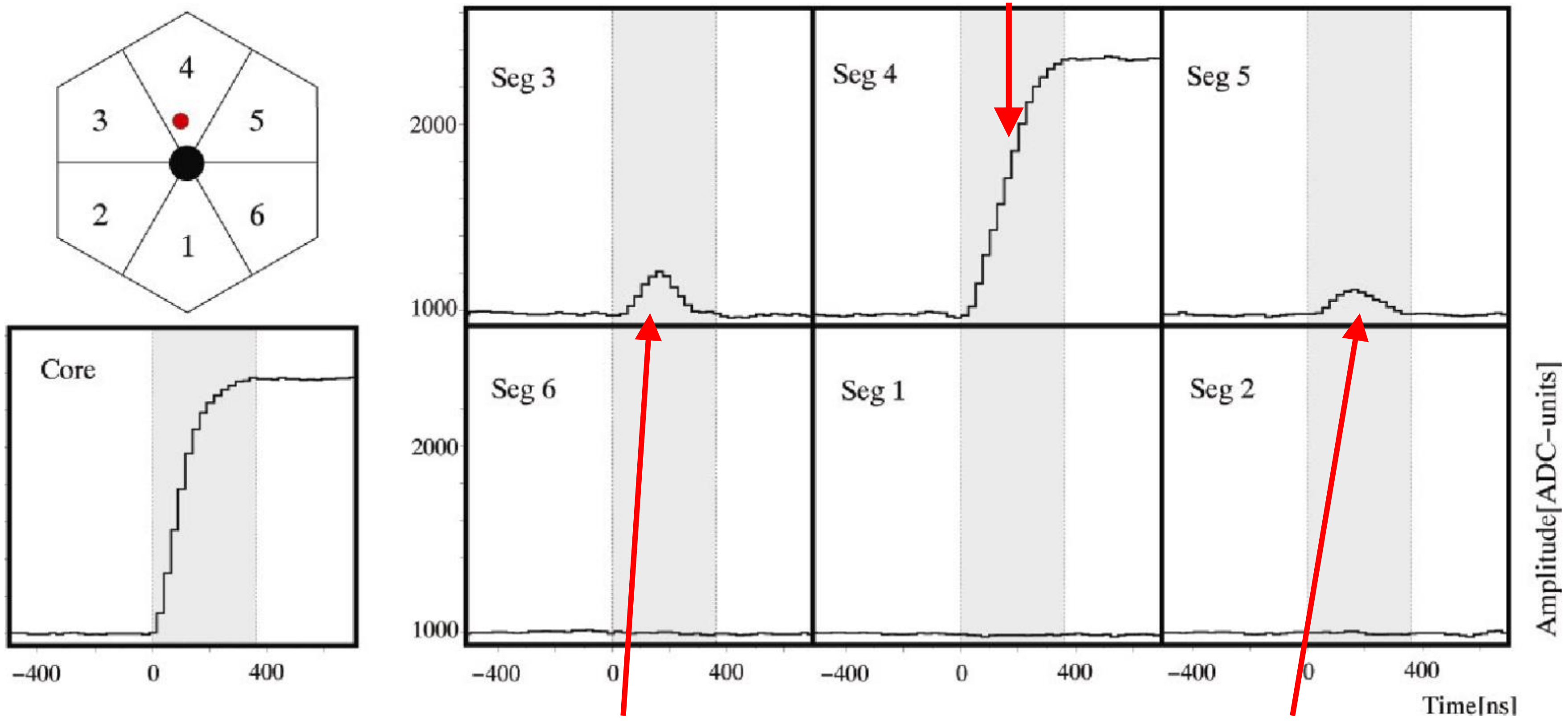
- When one of the electrodes is (electrically) segmented, the motion of charges within one segment induces a transient signal also in the neighboring electrodes
- Contrary to the segment where the interaction takes place (the charge is released), the total collected charge in the neighboring electrodes is null
- The amplitude of the induced transient signals provides a convenient way to locate the interaction with sub-segment precision

Segmentation of an AGATA detector



Pulse Shape Analysis concept

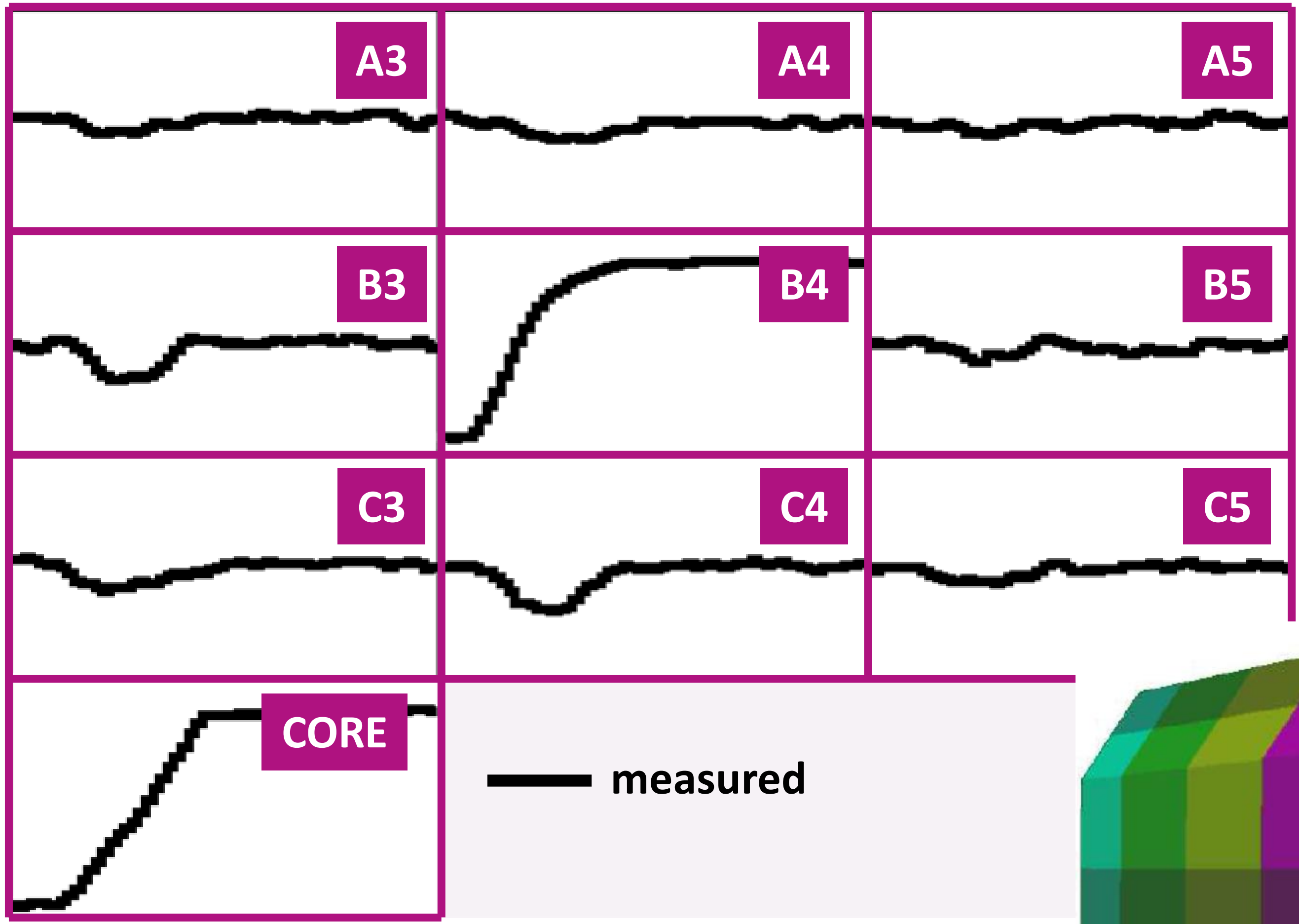
Interaction occurred in segment 4
(net charge signal)

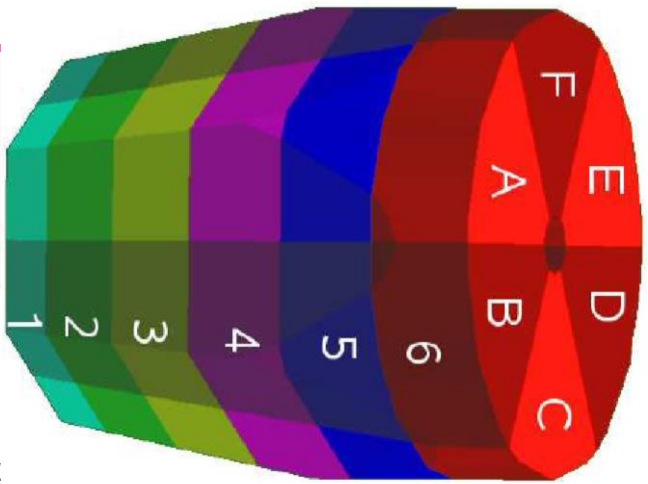


Interaction is closer to segment 3 (larger amplitude than segment 5)

Sub-segment precision … but not enough to efficiently perform tracking!
➔ Pulse Shape Analysis

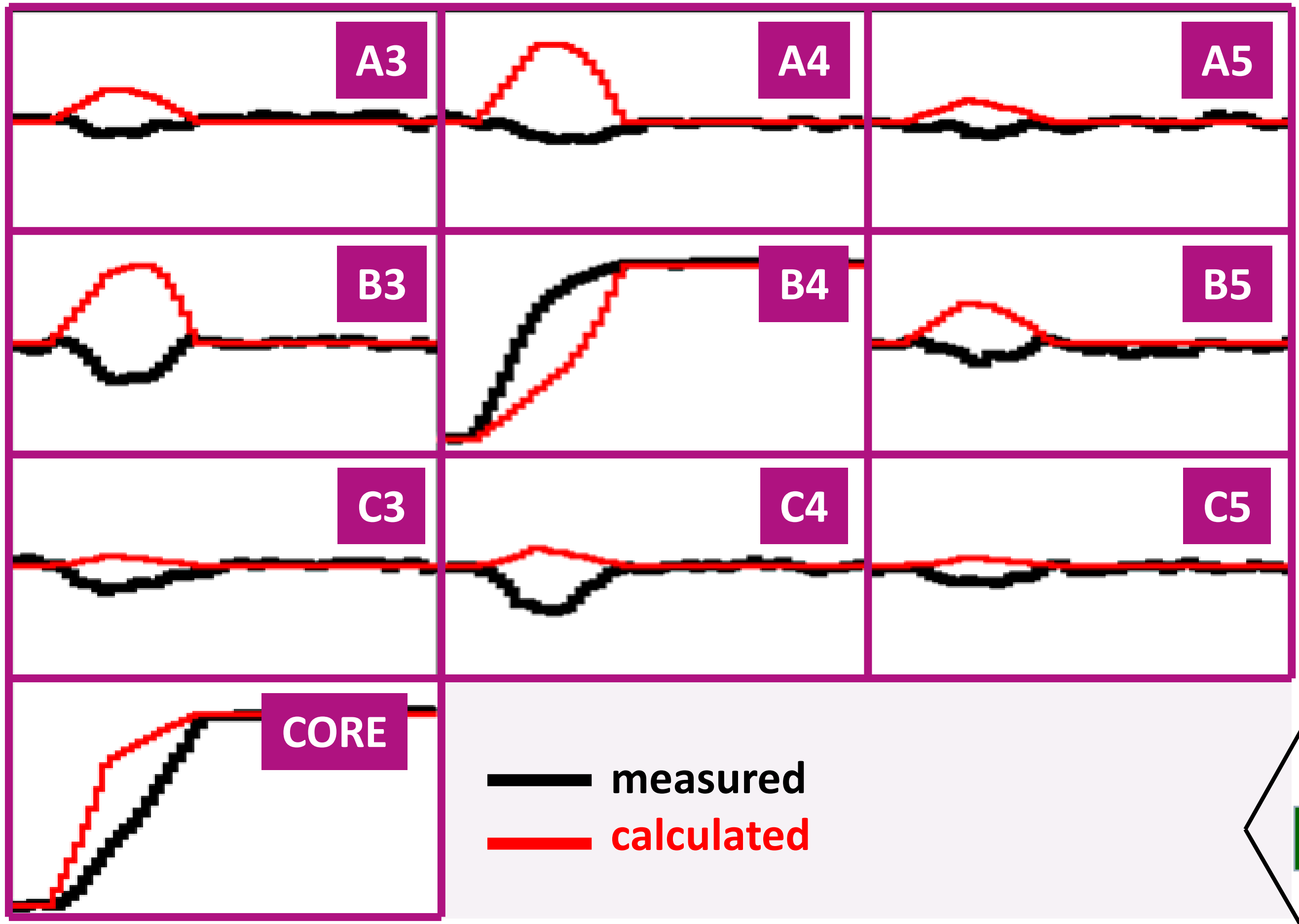
Pulse Shape Analysis concept

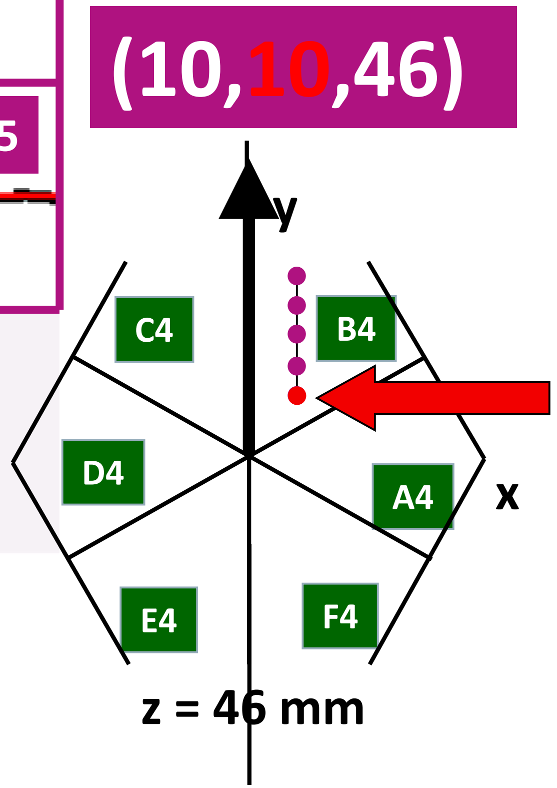




791 keV deposited in segment B4

Pulse Shape Analysis concept





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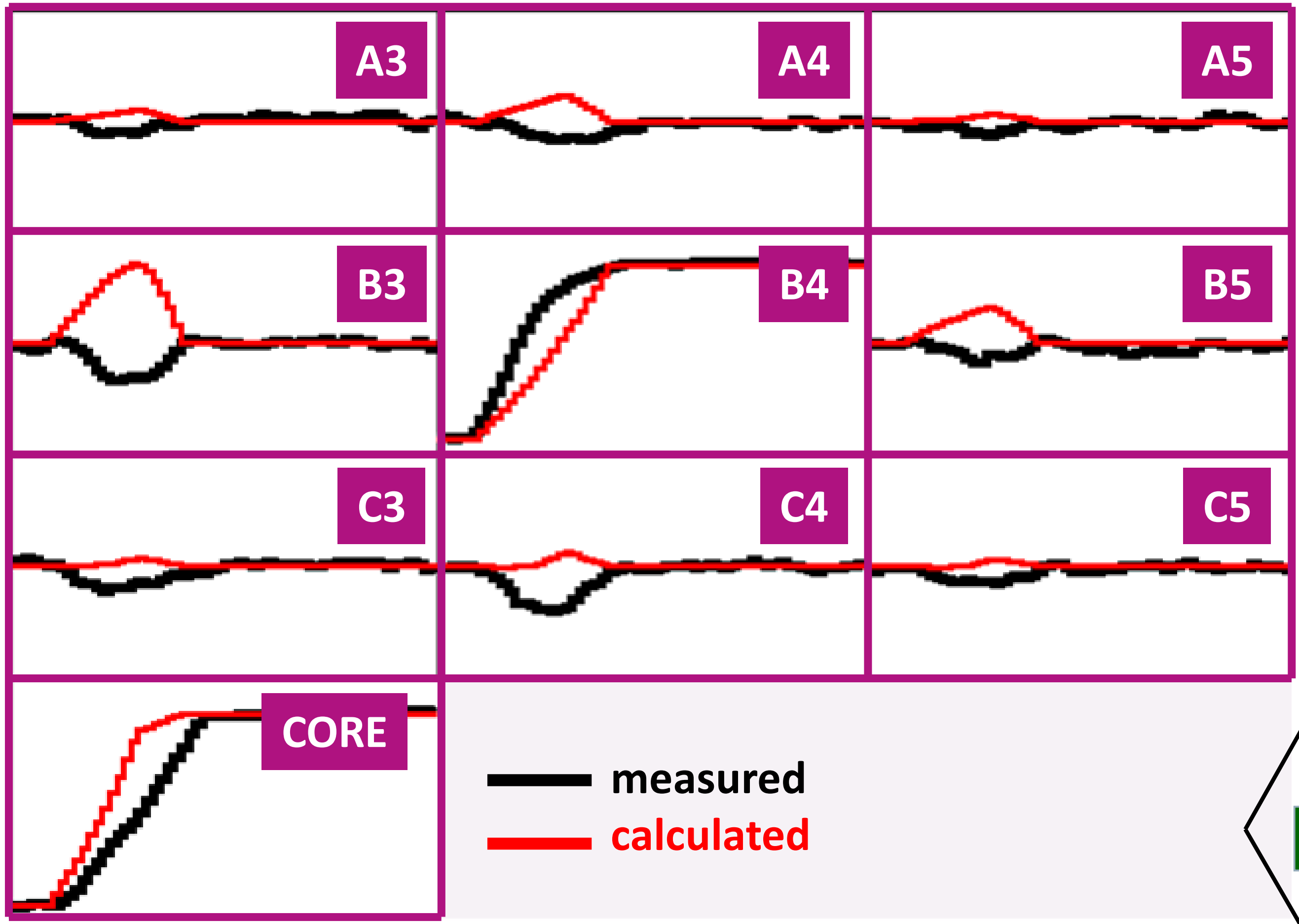

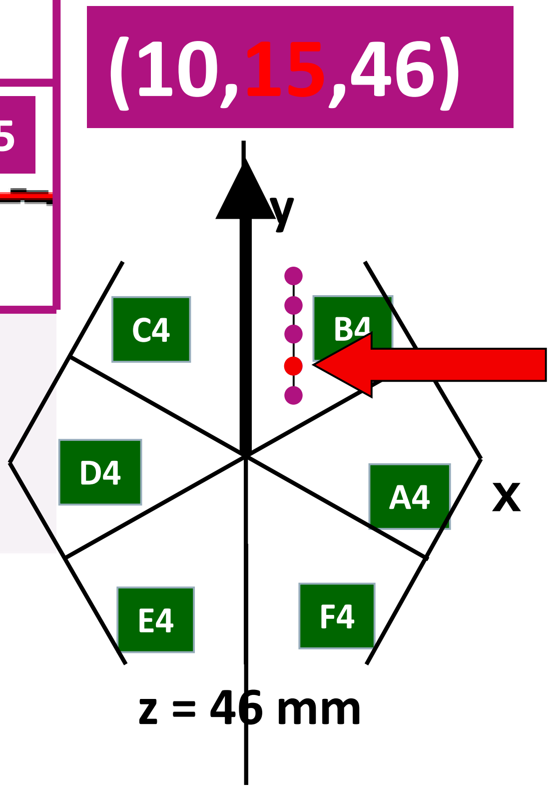

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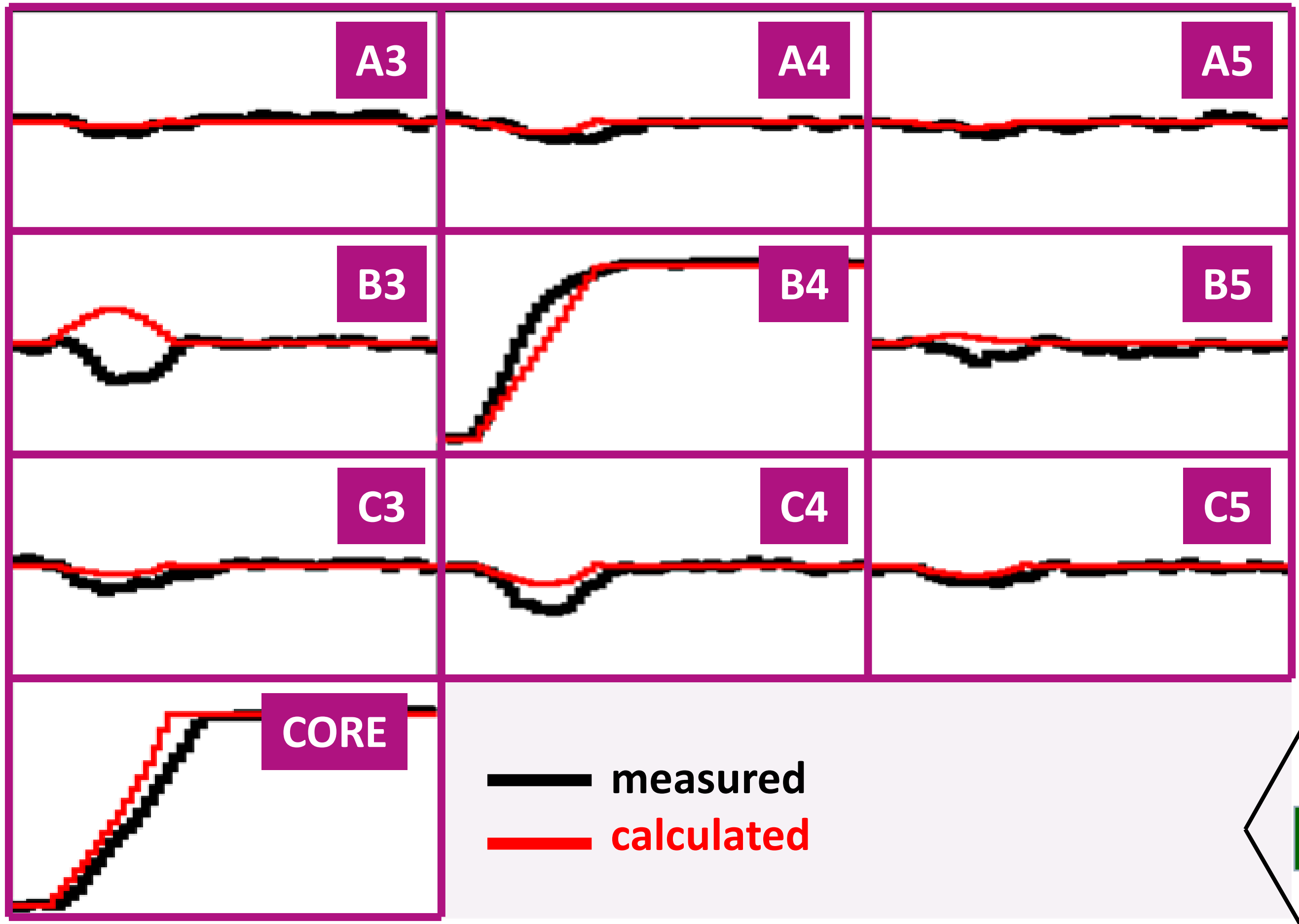
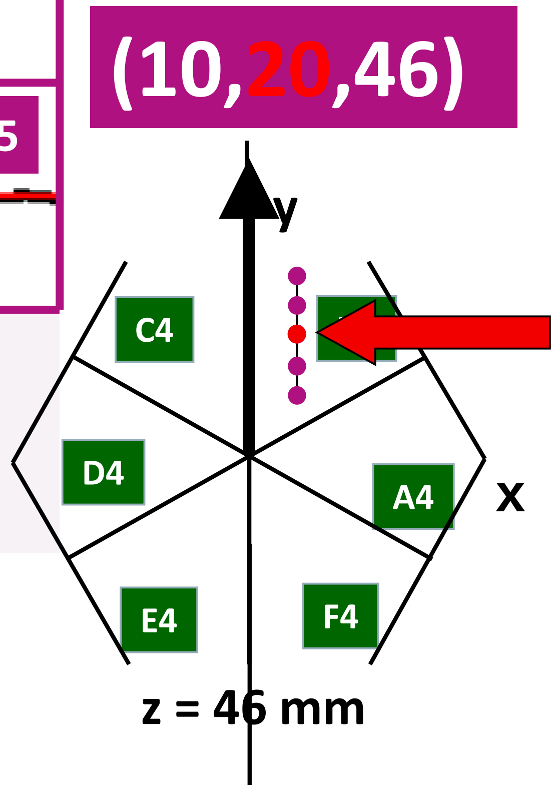
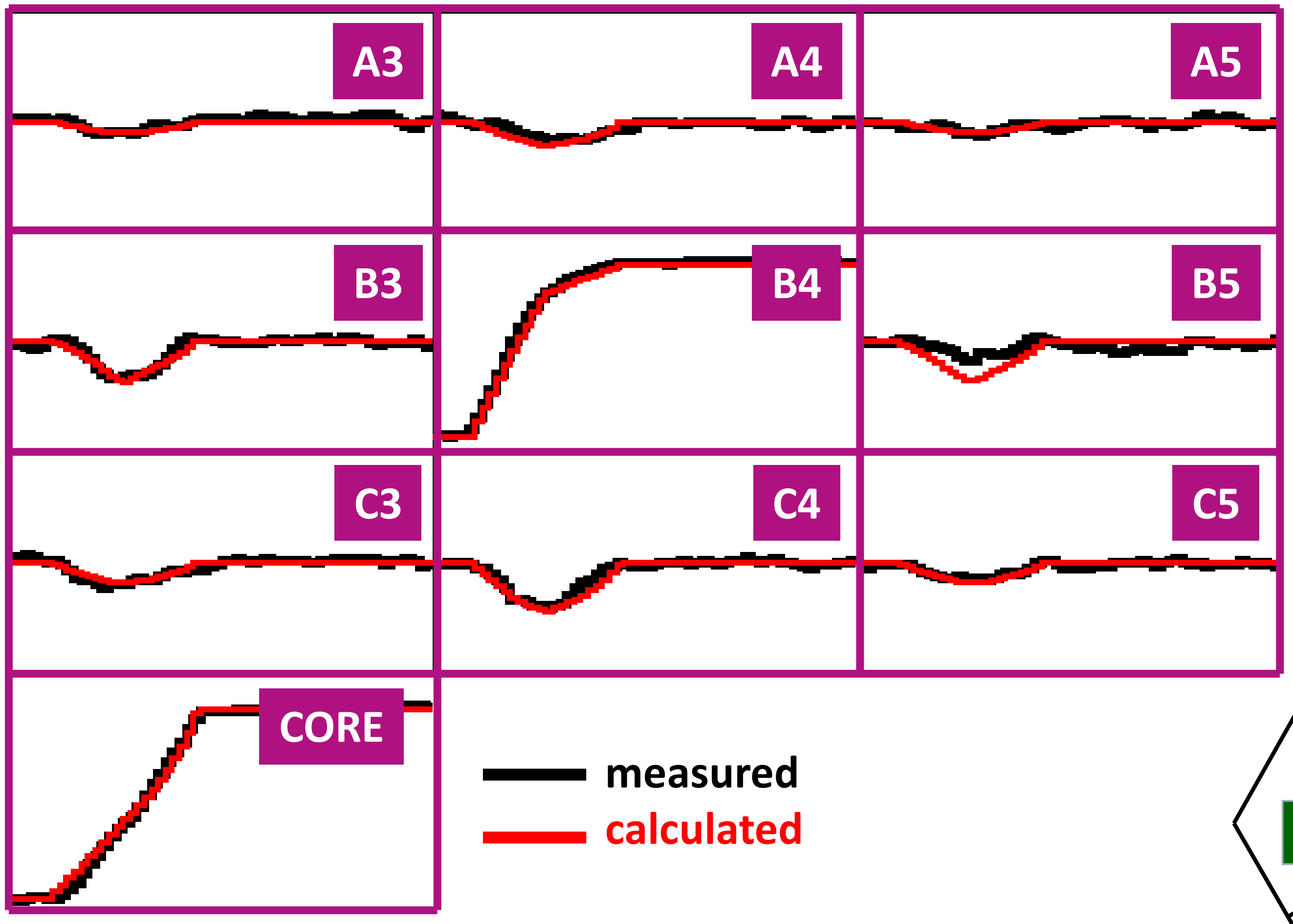
Pulse Shape Analysis concept

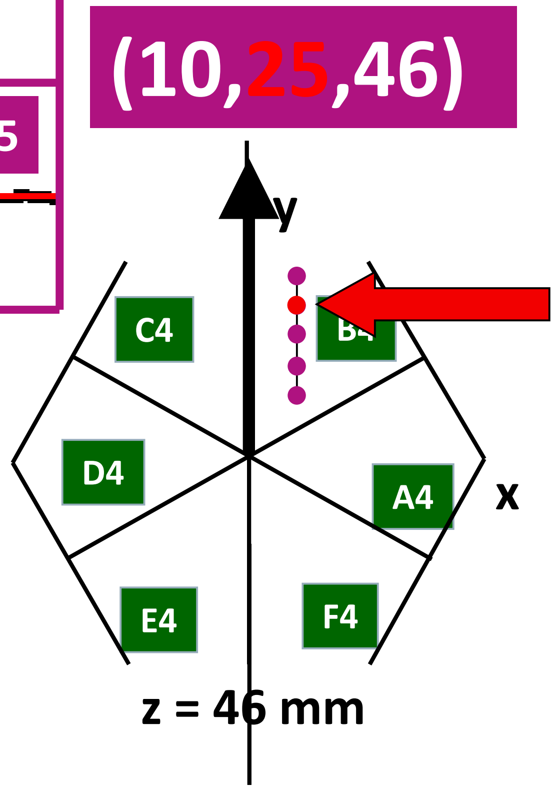




791 keV deposited in segment B4

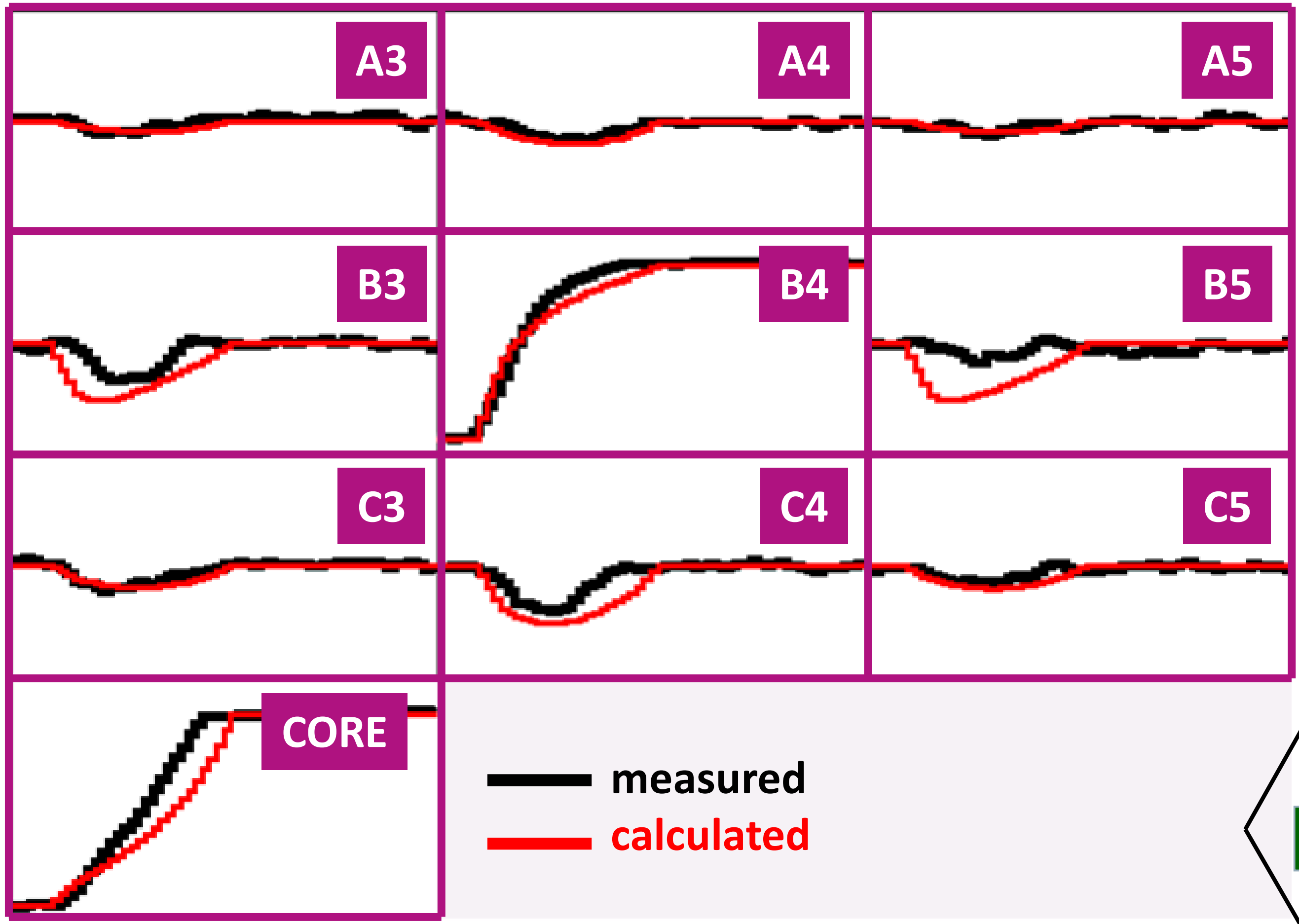
Pulse Shape Analysis concept

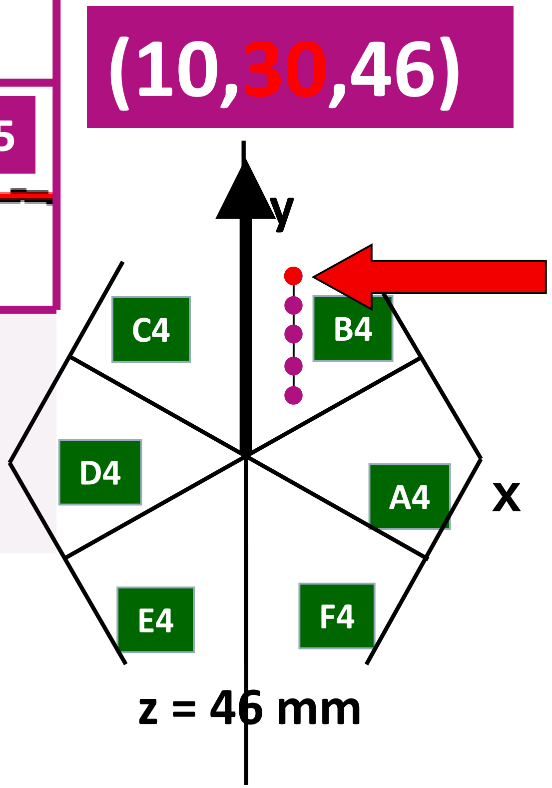




791 keV deposited in segment B4

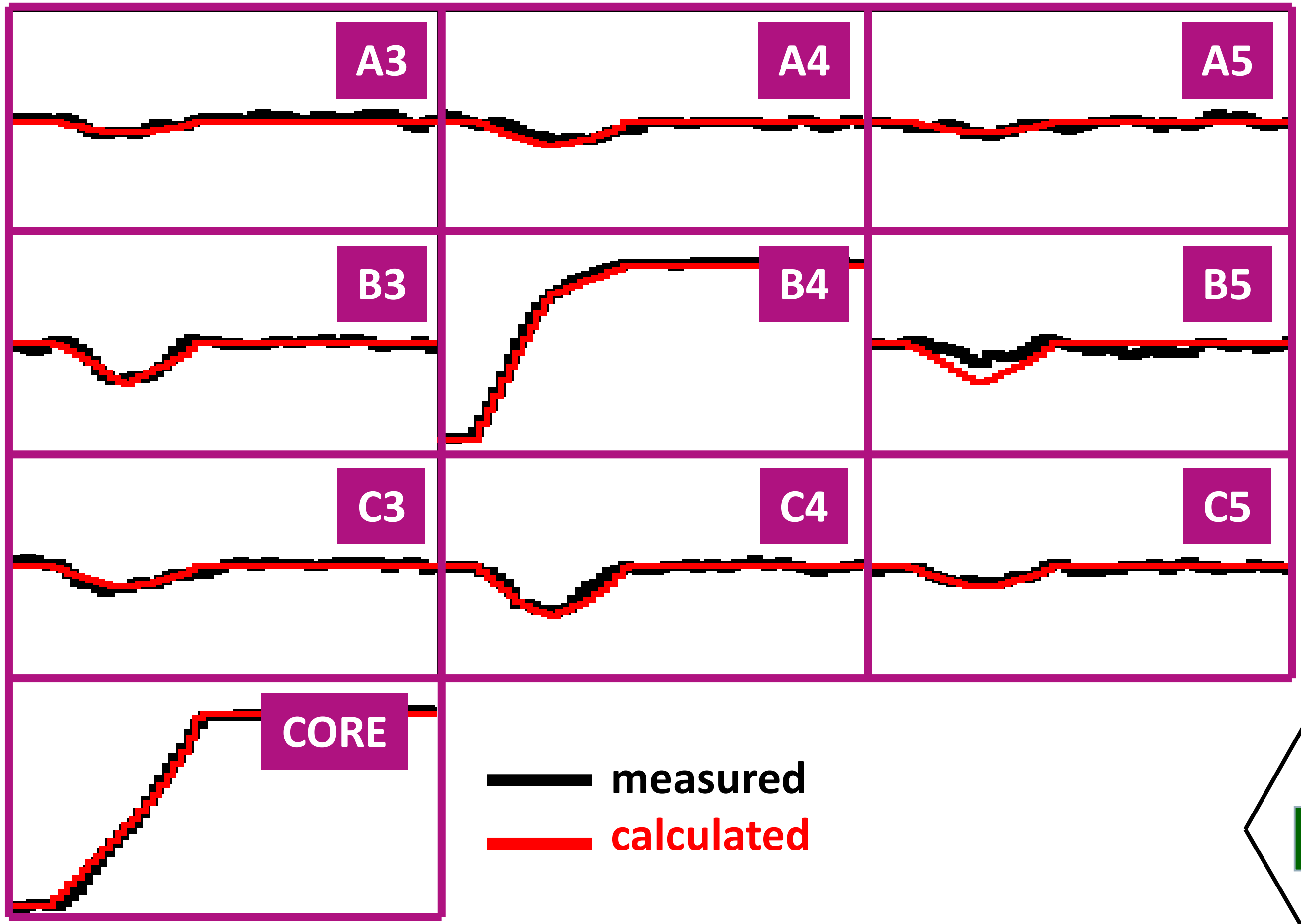
Pulse Shape Analysis concept





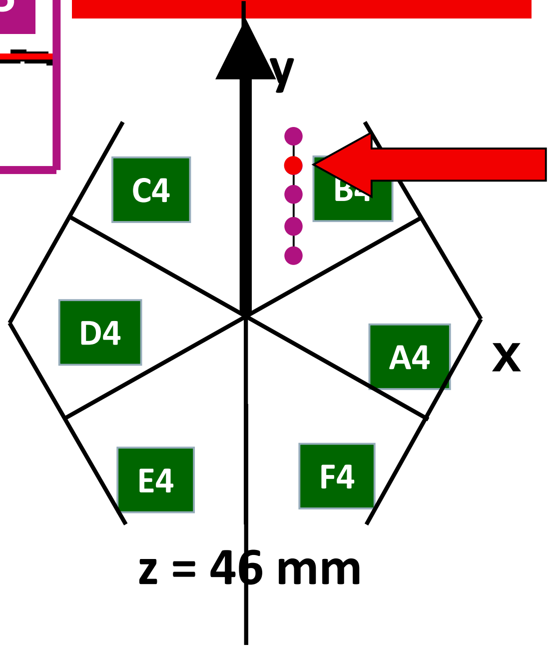
791 keV deposited in segment B4

Pulse Shape Analysis concept



Result of
Grid Search
Algorithm

(10,25,46)

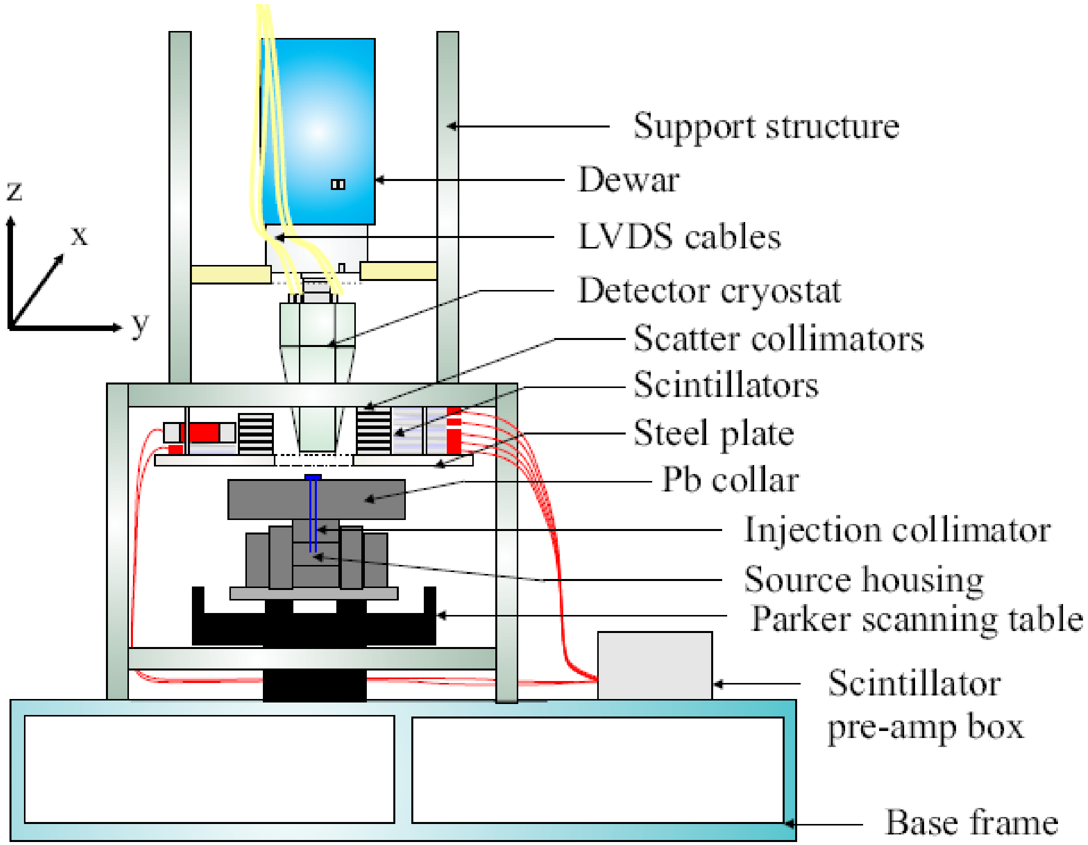


791 keV deposited in segment B4

Scan setup

- The interaction point is located by requesting a coincidence between the germanium detector and a second, narrowly collimated detector

- Scanning the whole crystal is a time-consuming procedure!

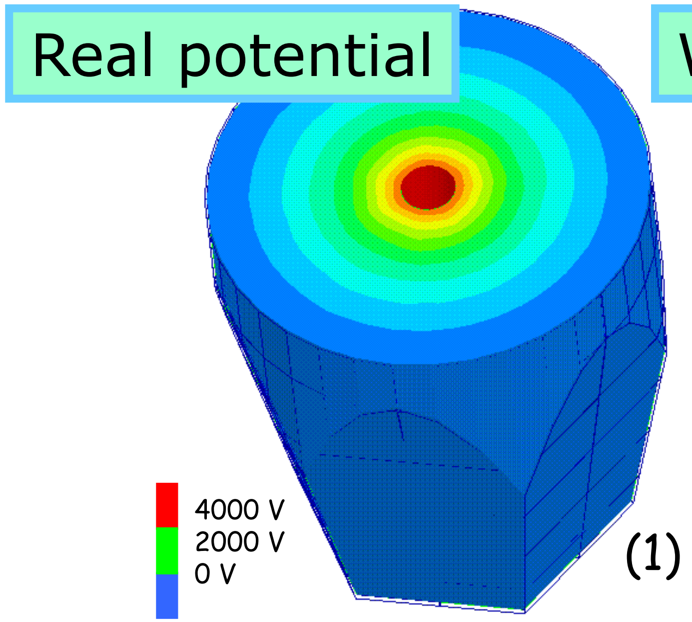


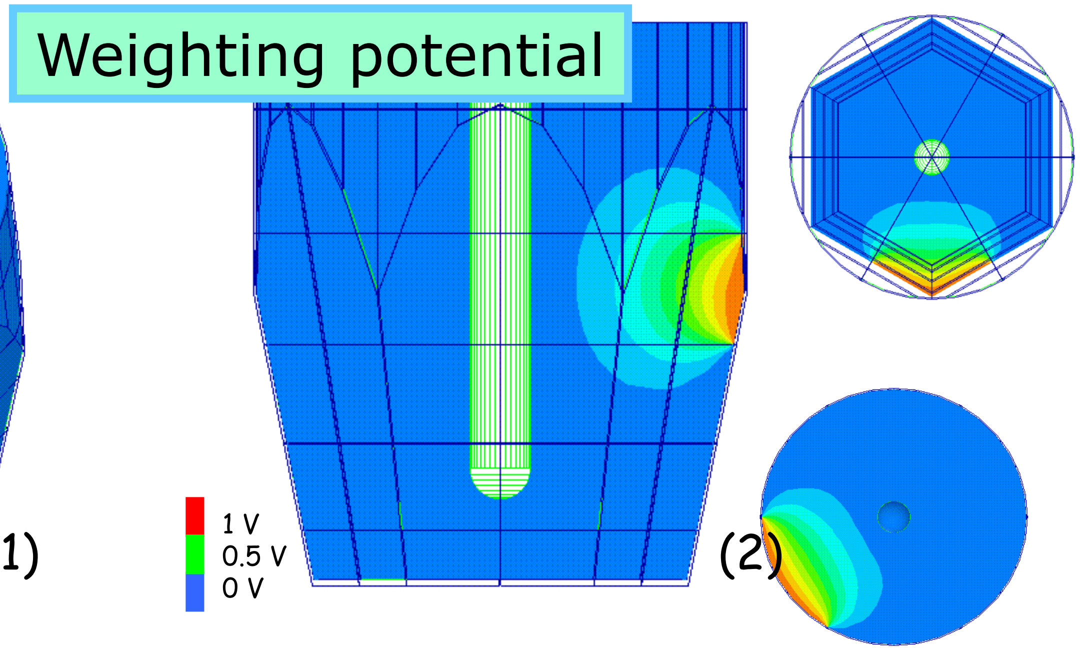
Signal Formation

- Signal is due to the **motion of charge carriers** inside the detector volume.
- Calculations based on the weighting field method derived by **Ramo's theorem**, which is based on
- Green's reciprocity theorem that says: given two systems consisting of a distribution of charges and electrodes, charges and voltages are related by

$$\boxed{\sum_i V_i Q_i' = \sum_i V_i' Q_i}$$

$$\left(\begin{array}{l} \text{For elementary charges one has} \\ V_i = \sum_{j \neq i} \frac{Q_j}{r_{ij}} \;\&\; V_i' = \sum_{j \neq i} \frac{Q_j'}{r_{ij}'} \quad \Rightarrow \quad \sum_i \sum_{j \neq i} \frac{Q_j}{r_{ij}} Q_i' = \sum_i \sum_{j \neq i} \frac{Q_j'}{r_{ij}'} Q_i \end{array} \right)$$





$$i_k = -q\vec{v} \cdot \vec{\nabla}\phi_k(r_q)$$

Current of electrode *k*

Weighting potential

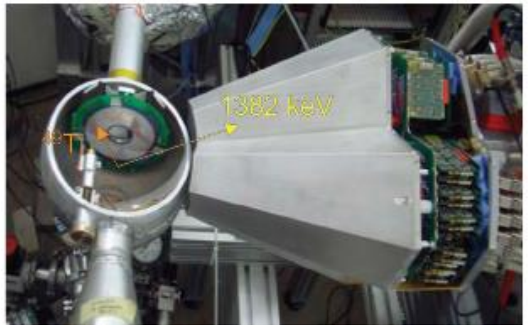
- Weighting potential is calculated by applying 1 V on the segment collecting the charge and 0 V to all the others (Ramo's Theorem).
- It measures the electrostatic coupling (induced charge) between the moving charge and the sensing contact.

Position resolution for AGATA

Method = Doppler correction capability in an in-beam experiment

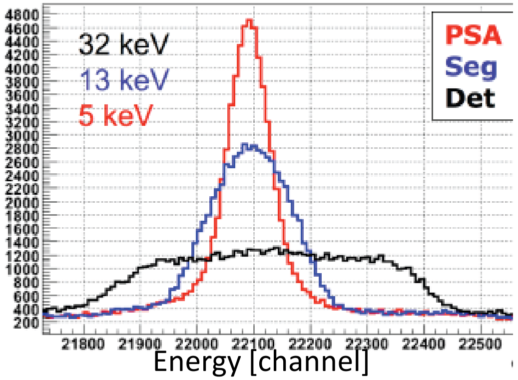
F. Recchia et al., NIMA 604 (2009) 555

P-A. Soederstroem et al., NIMA 638 (2011) 96



REACTION CHANNEL: $^{48}Ti(d,p)^{49}Ti$

beam	^{48}Ti	100 MeV
target	^{48}Ti + ^{2}H	220 μg/cm²
Si detector	thickness	300 μm
	segmentation	32 rings, 64 sectors
AGATA triple symmetric cluster		



F. Recchia et al., NIMA 604 (2009) 555

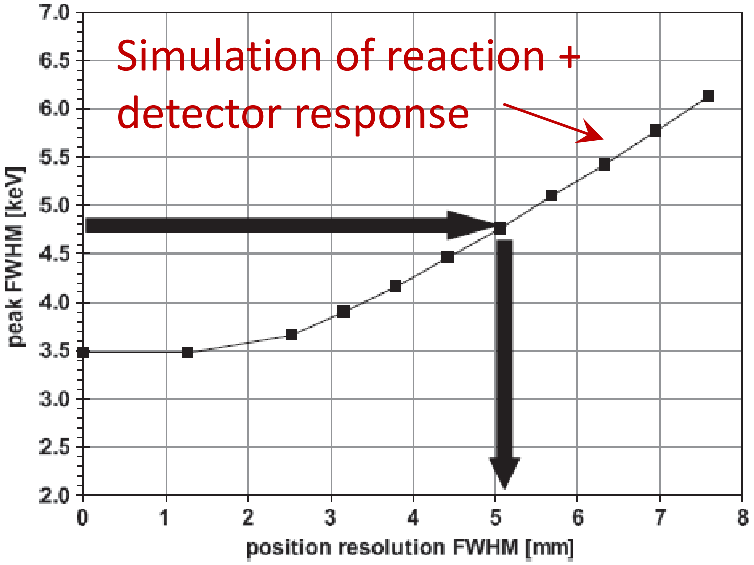
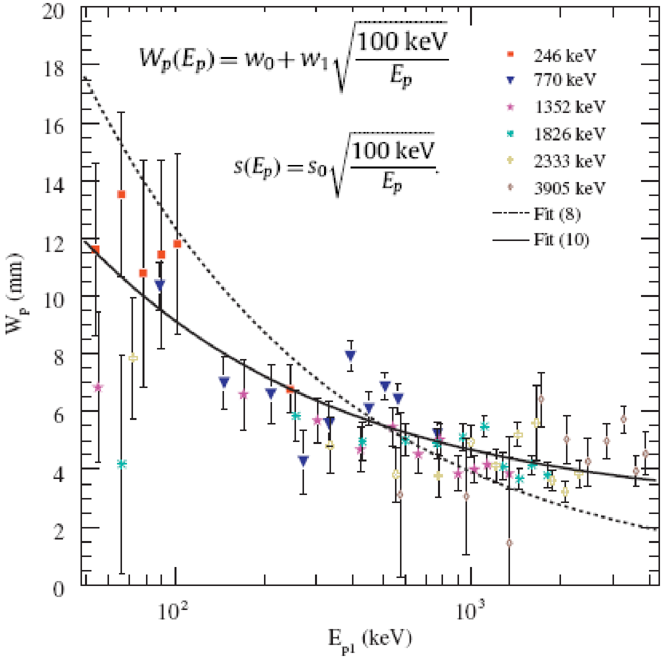


Fig. 10. Width of the simulated 1382 keV peak as a function of the position smearing for the full triple cluster. Individual crystal energy resolution have been considered. All of the segment multiplicities are taken into account. The horizontal arrow indicates the experimental width.



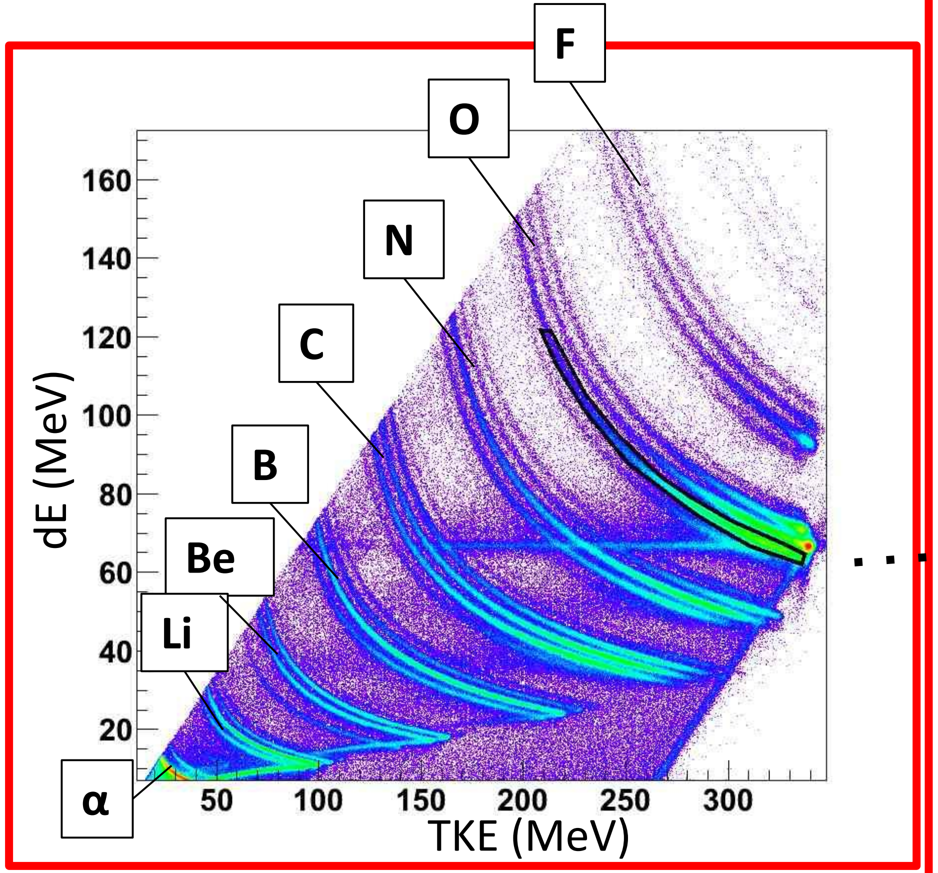
U R C E

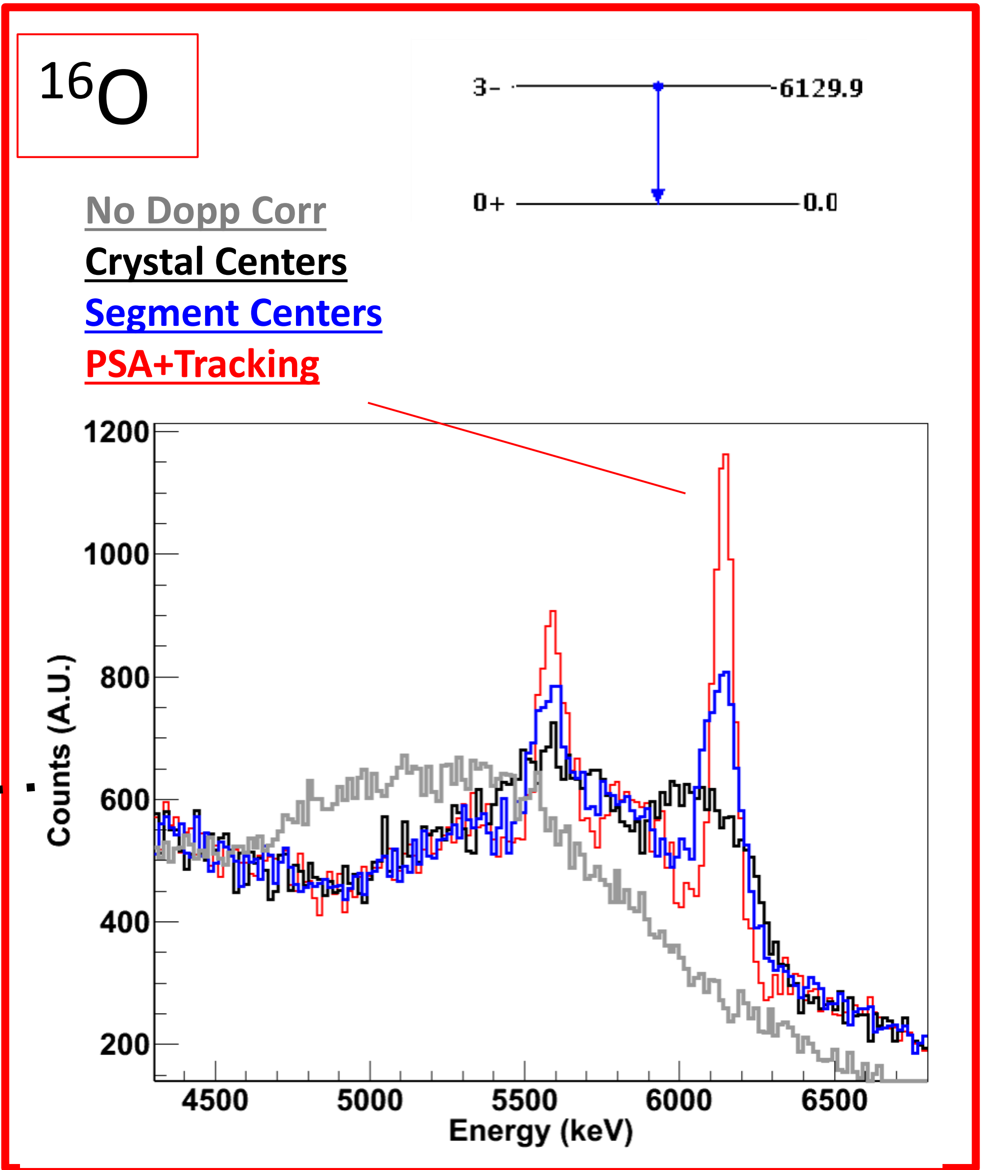
NEUTRONS FOR SOCIETY

Doppler correction capabilities

AGATA Demonstrator at LNL

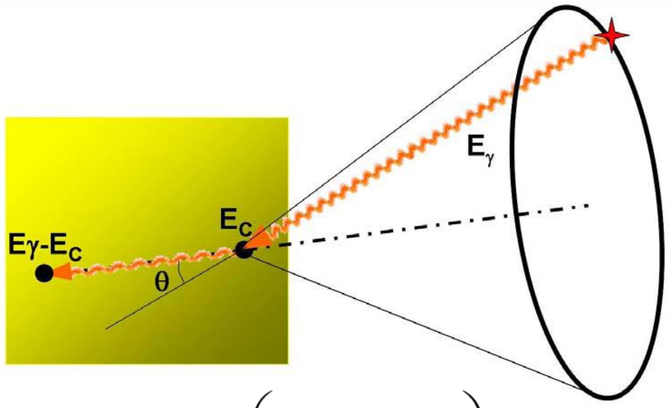
Inelastic scattering
^{17}O @ 20 MeV/u on ^{208}Pb



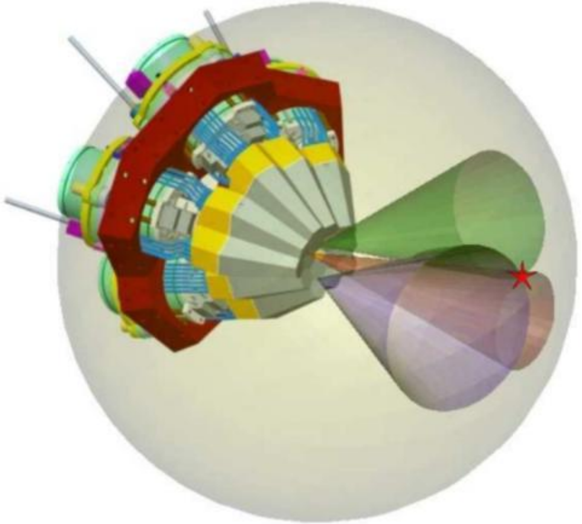


F.Crespi, Milano

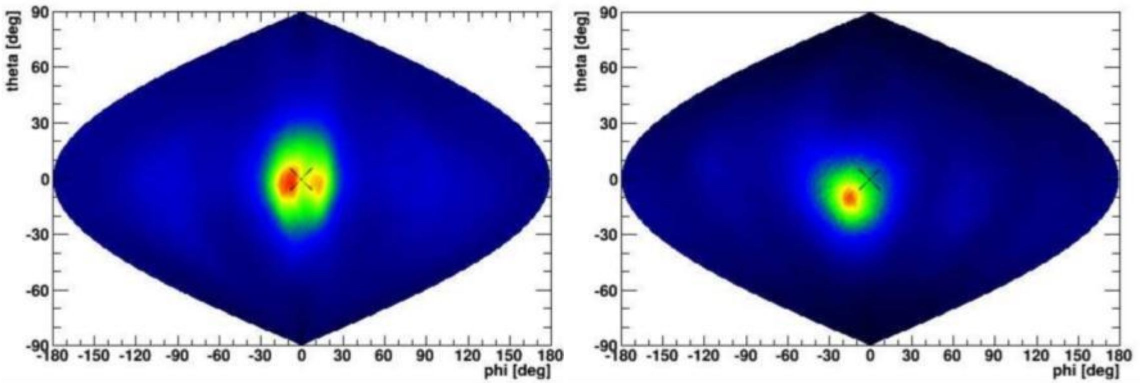
AGATA as a big (and expensive) Compton camera



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



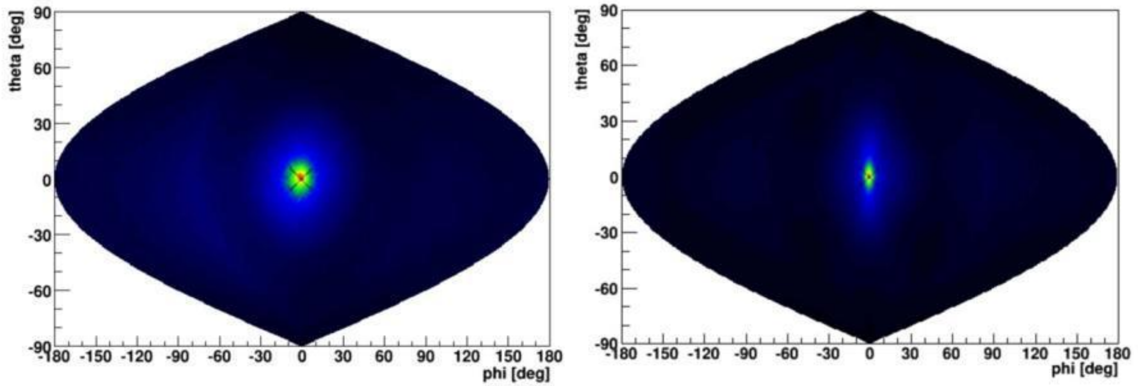
Far Field Backprojection



All 9 detectors

One detector

Near Field Backprojection



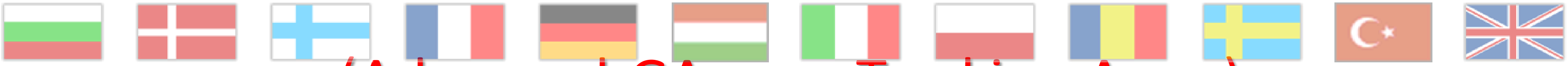
All 9 detectors

One detector

Source at 51 cm ➔Dx ~Dy ~2 mm Dz ~2 cm

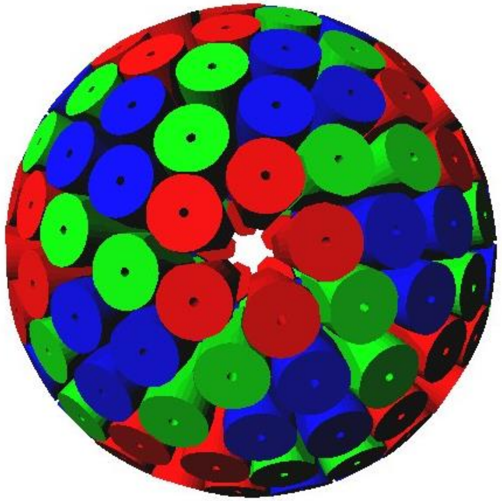
F. Recchia et al., NIMA 604 (2009) 60

AGATA



(Advanced-GAmma-Tracking-Array)

the "γ-ray spectroscopy dream"

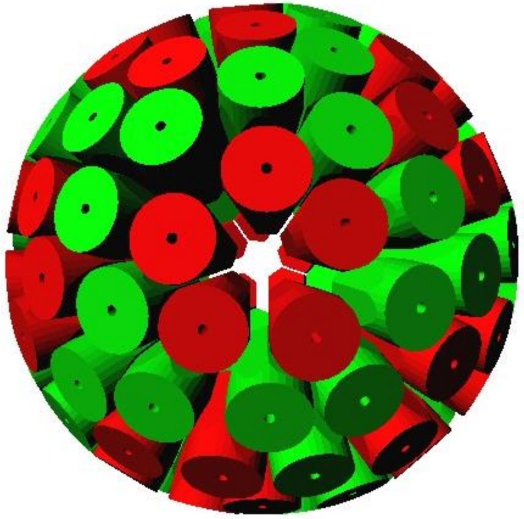


- High efficiency.
- Good position resolution on the individual γ interactions.
- Capability to stand a high counting rate.
- High granularity.
- Capability to measure the Compton scattering angles of the γ-rays within the detectors.
- Coupling to ancillary devices for added selectivity.

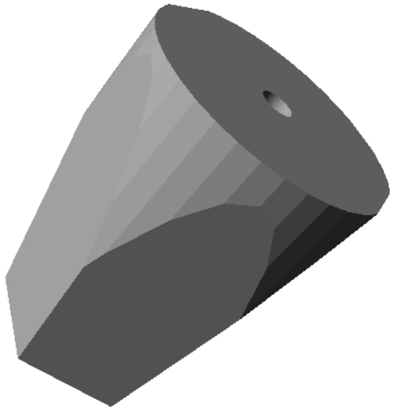
180 hexagonal crystals	3 shapes
60 triple clusters	all equal
inner radius	24 cm
amount of germanium	374 kg
solid angle coverage	79 %
6480 segments	
efficiency at 1MeV:	39% (M_g=1), 25% (M_g=30)
Peak/Total:	53% (M_g=1), 46% (M_g=30)

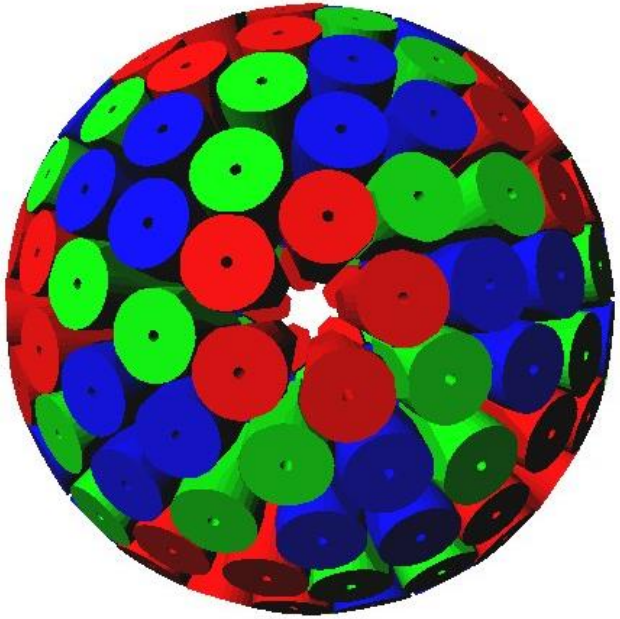
Geant4 Montecarlo simulations
E. Farnea, NIMA 621 (2010) 331

GRETA vs. AGATA



Ge crystals size:
Length 90 mm
Diameter 80 mm

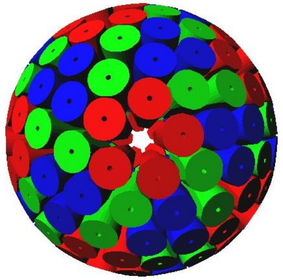


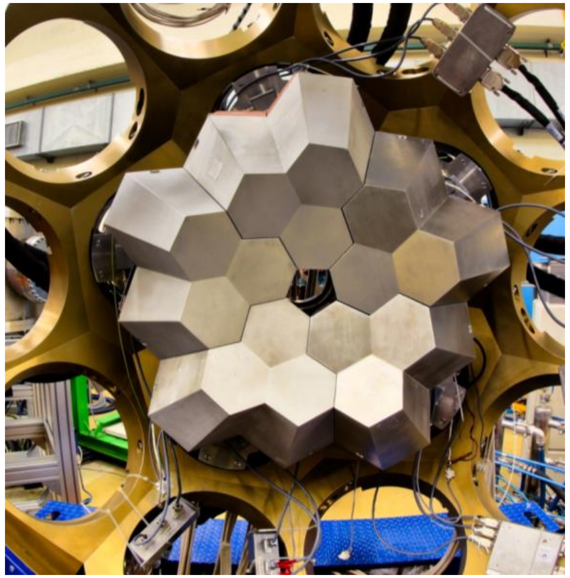


120 hexagonal crystals 2 shapes
30 quadruple-clusters all equal
Inner radius (Ge) 18.5 cm
Amount of germanium 237 kg
Solid angle coverage 81 %
4320 segments
Efficiency: 41% (M_γ=1) 25% (M_γ=30)
Peak/Total: 57% (M_γ=1) 47% (M_γ=30)

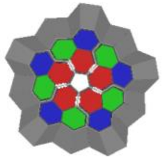
180 hexagonal crystals 3 shapes
60 triple-clusters all equal
Inner radius (Ge) 23.5 cm
Amount of germanium 362 kg
Solid angle coverage 82 %
6480 segments
Efficiency: 43% (M_γ=1) 28% (M_γ=30)
Peak/Total: 58% (M_γ=1) 49% (M_γ=30)

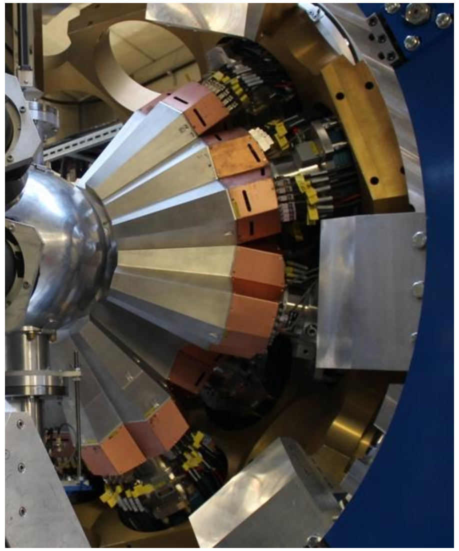
“realization of the dream”: AGATA the *nomadic detector*





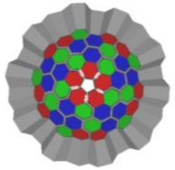
Demonstrator at the Legnaro National Lab., Italy
2009-2012

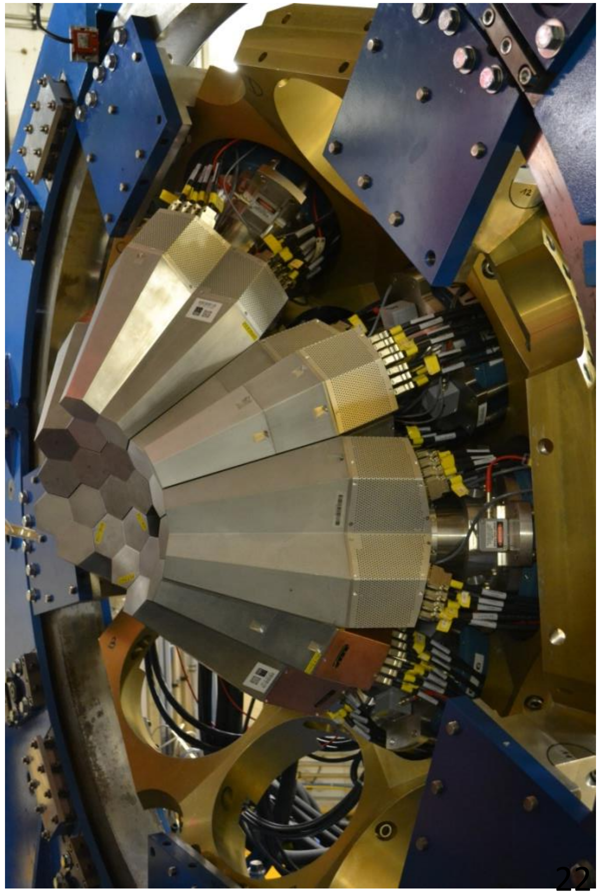




AGATA @ GSI
Germany
2012-2014

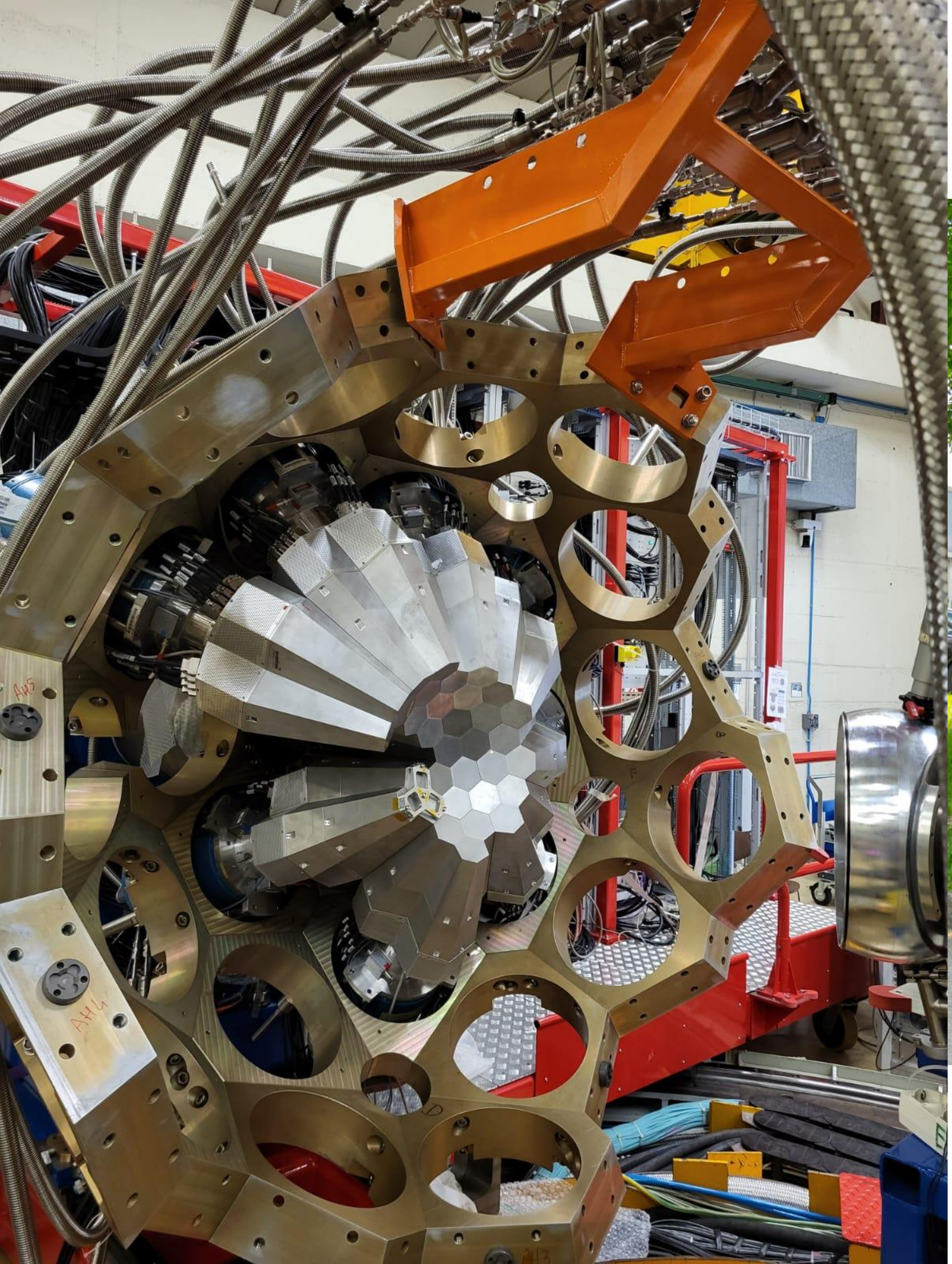
AGATA@GANIL,
2014-2020





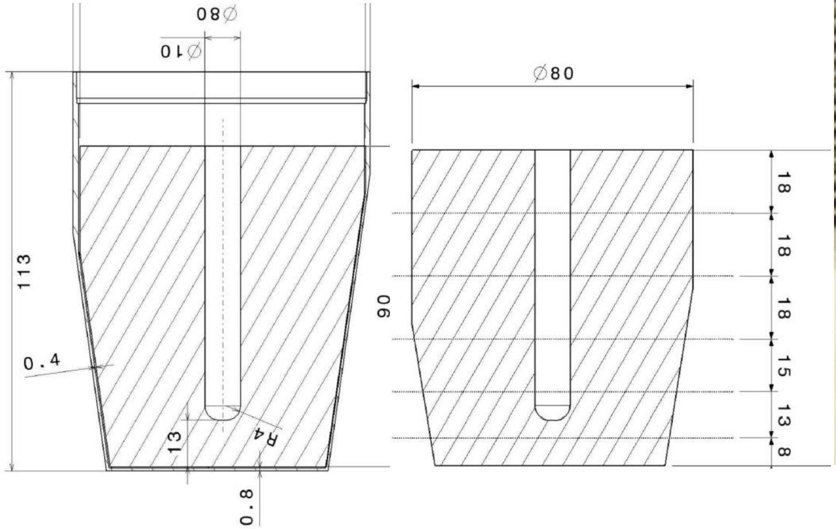
THE EURO

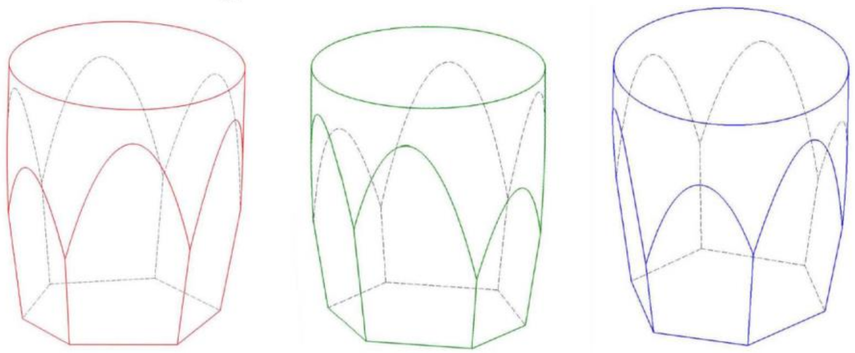
22



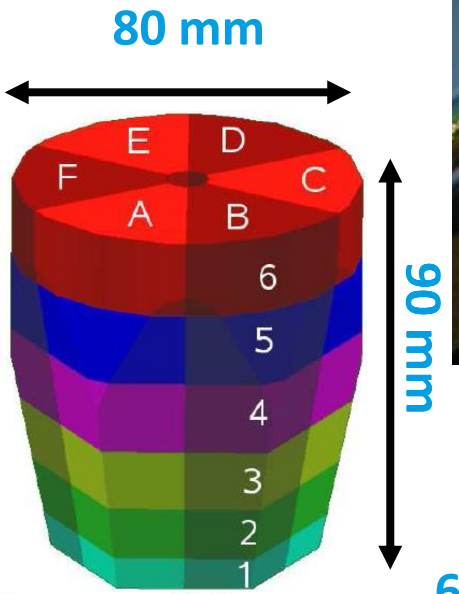
AGATA is today at LNL

AGATA Crystals





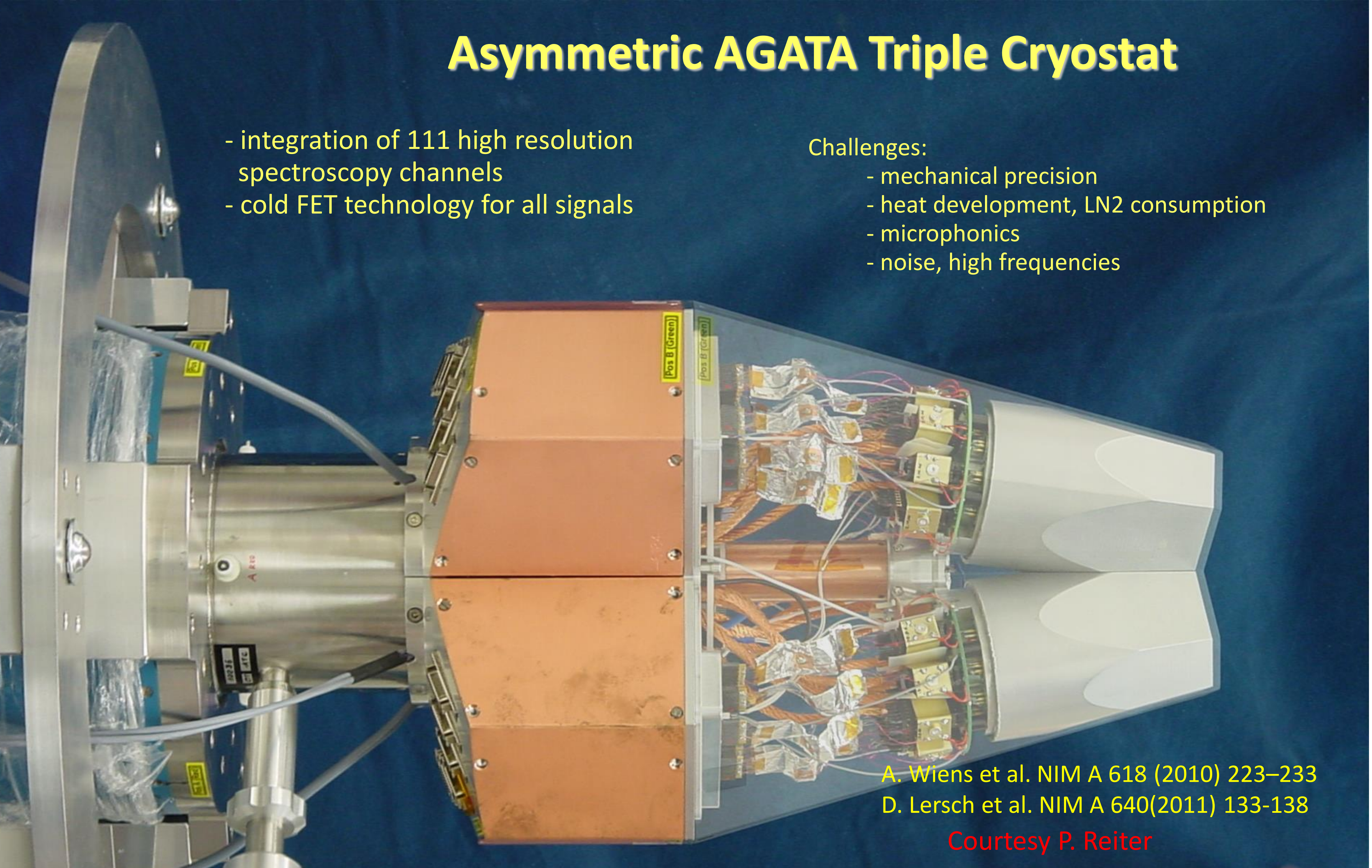
(d) A - red (e) B - green (f) C - blue



Volume ~370 cc Weight ~2 kg
(the 3 shapes are volume-equalized to 1%)

6x6 segmented cathode

Asymmetric AGATA Triple Cryostat



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

Challenges:

- mechanical precision
- heat development, LN2 consumption
- microphonics
- noise, high frequencies

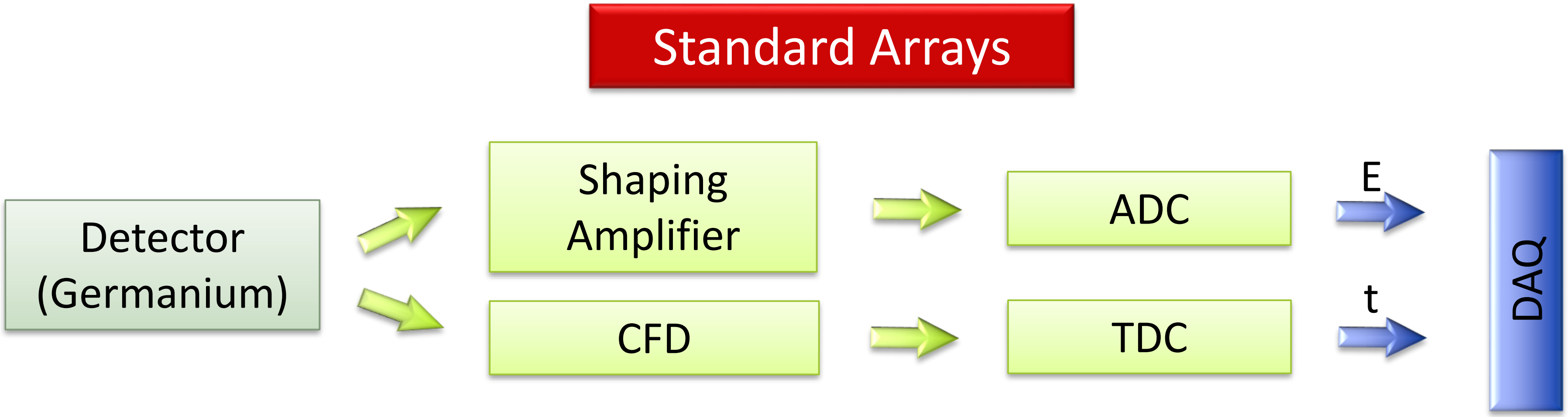
A. Wiens et al. NIM A 618 (2010) 223–233

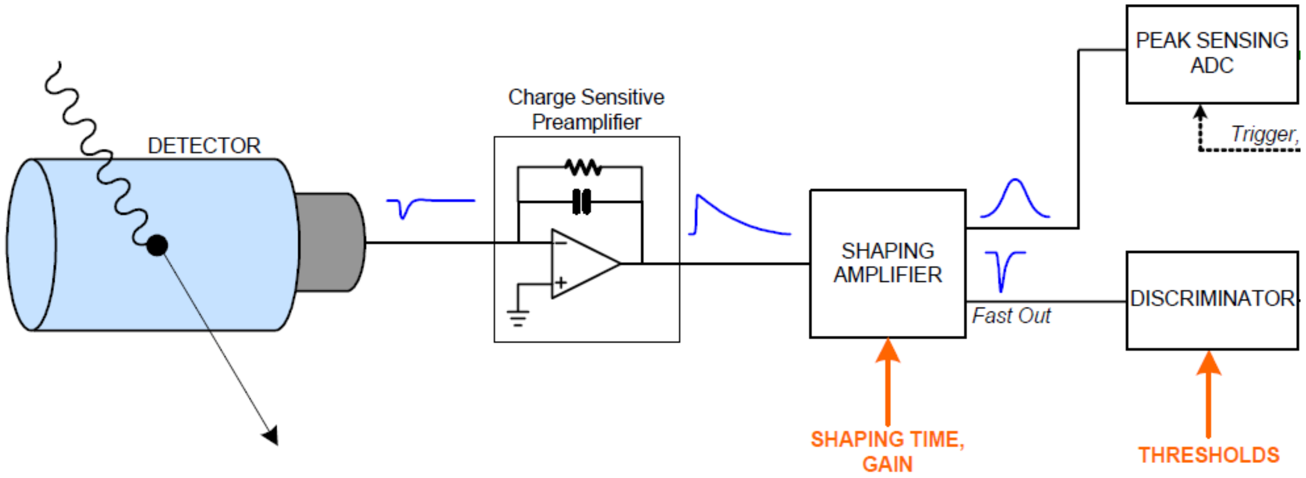
D. Lersch et al. NIM A 640(2011) 133-138

Courtesy P. Reiter

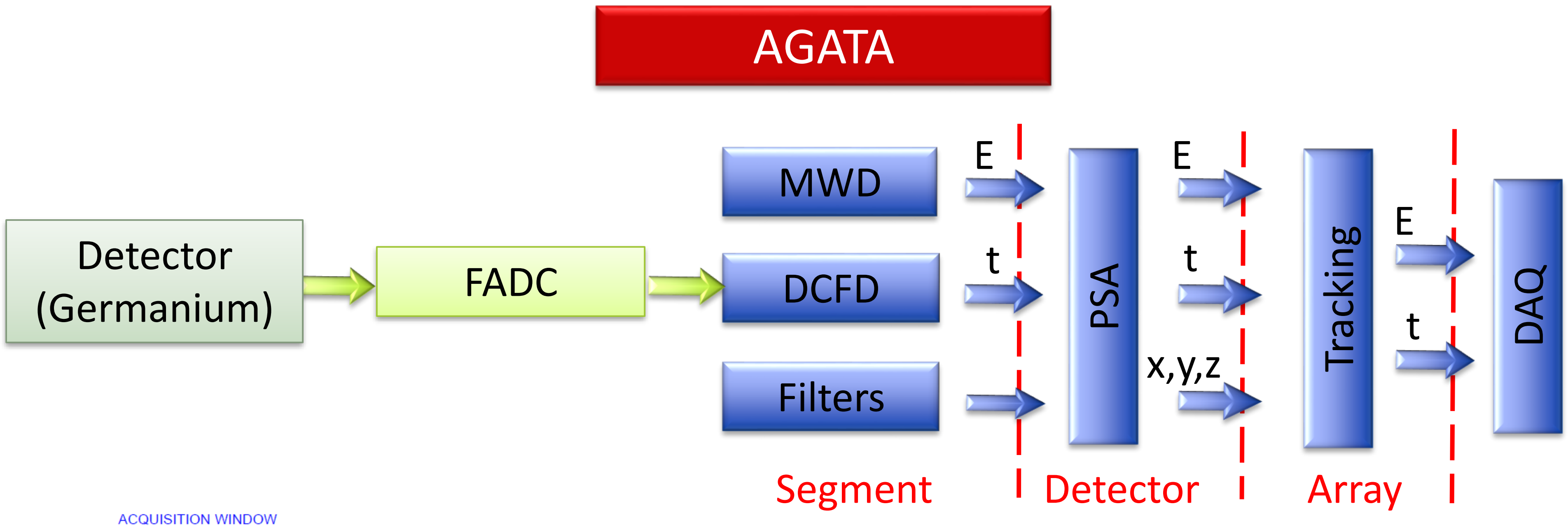
NEUTRONS FOR SOCIETY

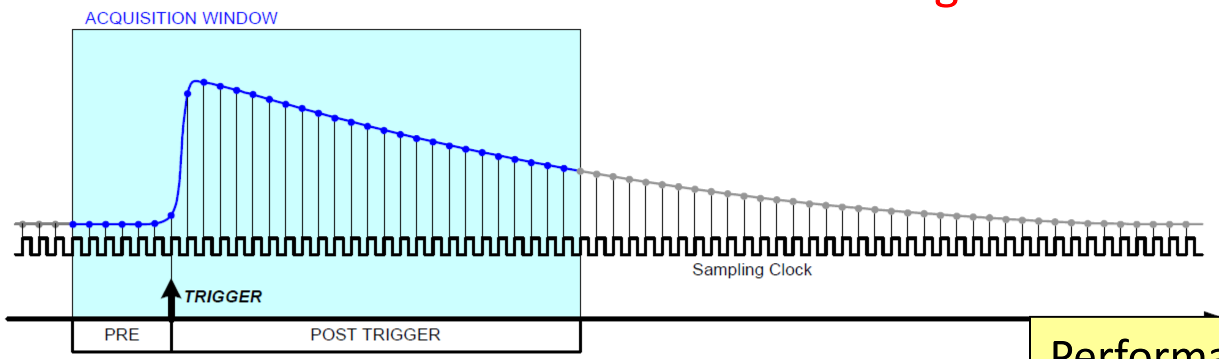
Analogue vs Digital Electronics





Analogue vs Digital Electronics





Performance comparable to best analog electronics.
Higher count rate capabilities

Digital processing of signals

The energy is obtained via trapezoidal filter (or *Moving Window Deconvolution, MWD*)

A.Georgiev and W. Gast, IEEE Trans. Nucl. Sci., 40(1993)770
V.T.Jordanov and G.F.Knoll, Nucl.Instr.Meth., A353(1994)261

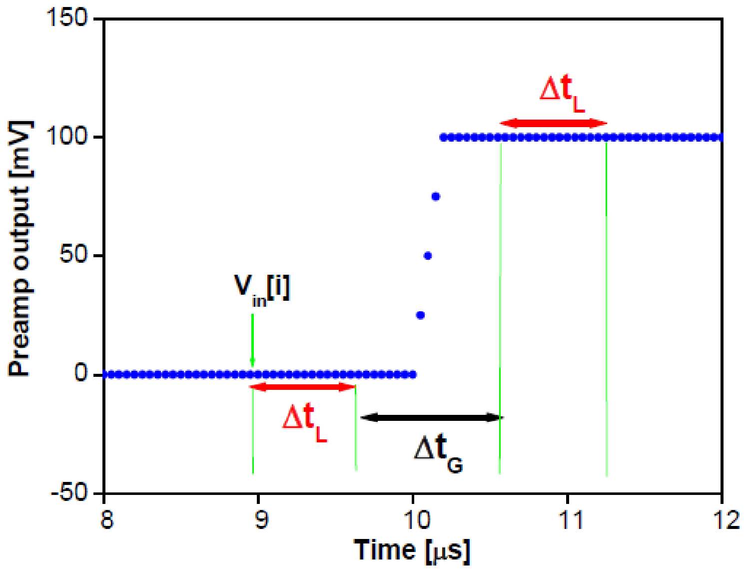


Fig. 6.26. Trapezoidal filter parameters.

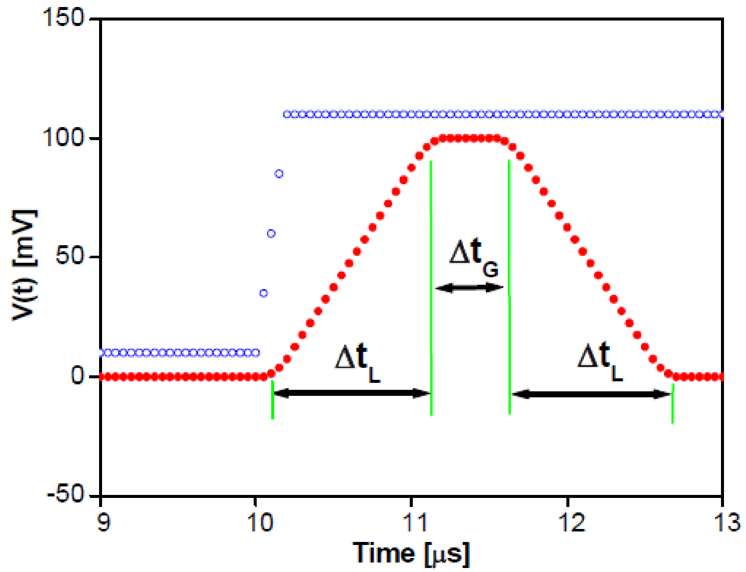


Fig. 6.27. Trapezoidal filter output.

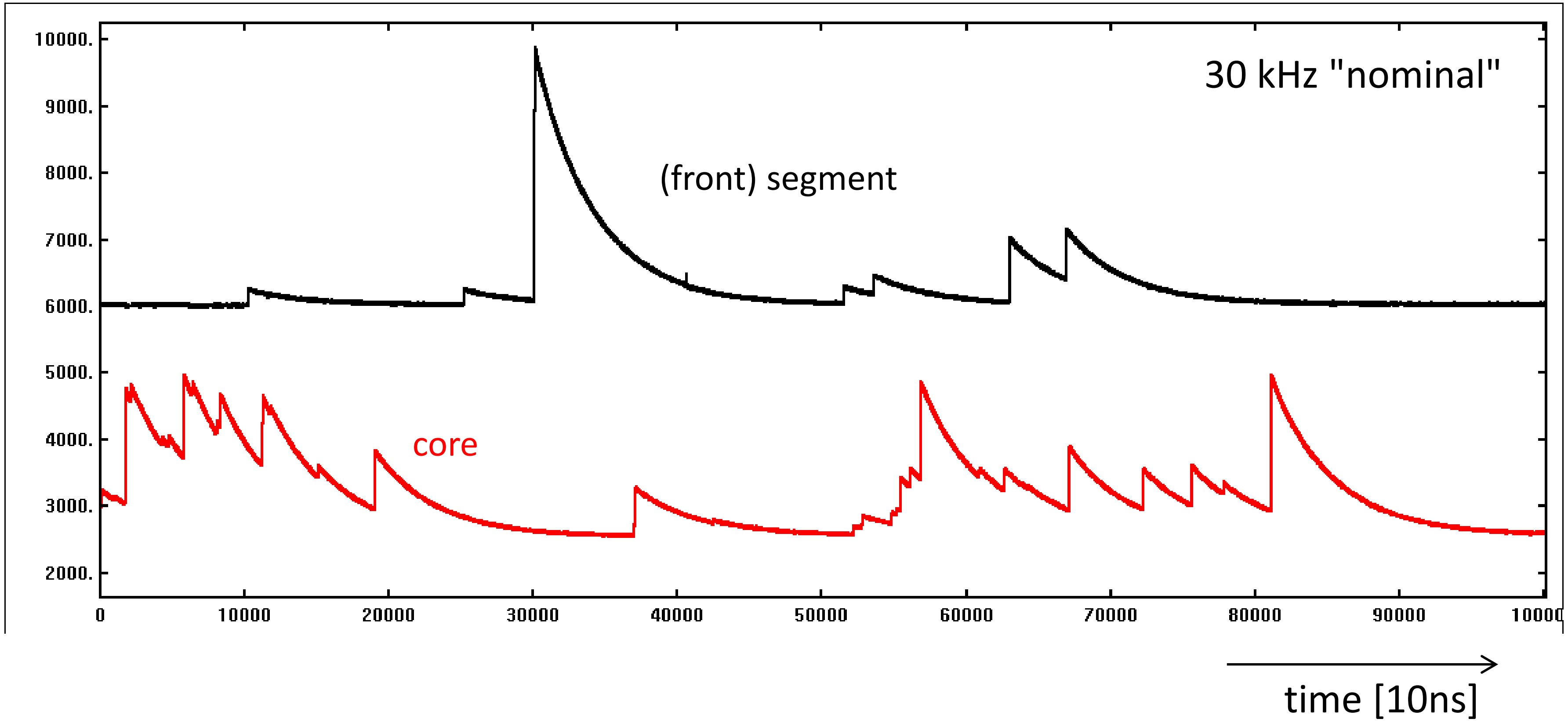
1) $$V_{av1}[i] = \frac{1}{L}\sum_{j=0}^{L-1} V_{in}[i+j]$$

2) $$V_{av2}[i] = \frac{1}{L}\sum_{j=0}^{L-1} V_{in}[L+G+i+j]$$

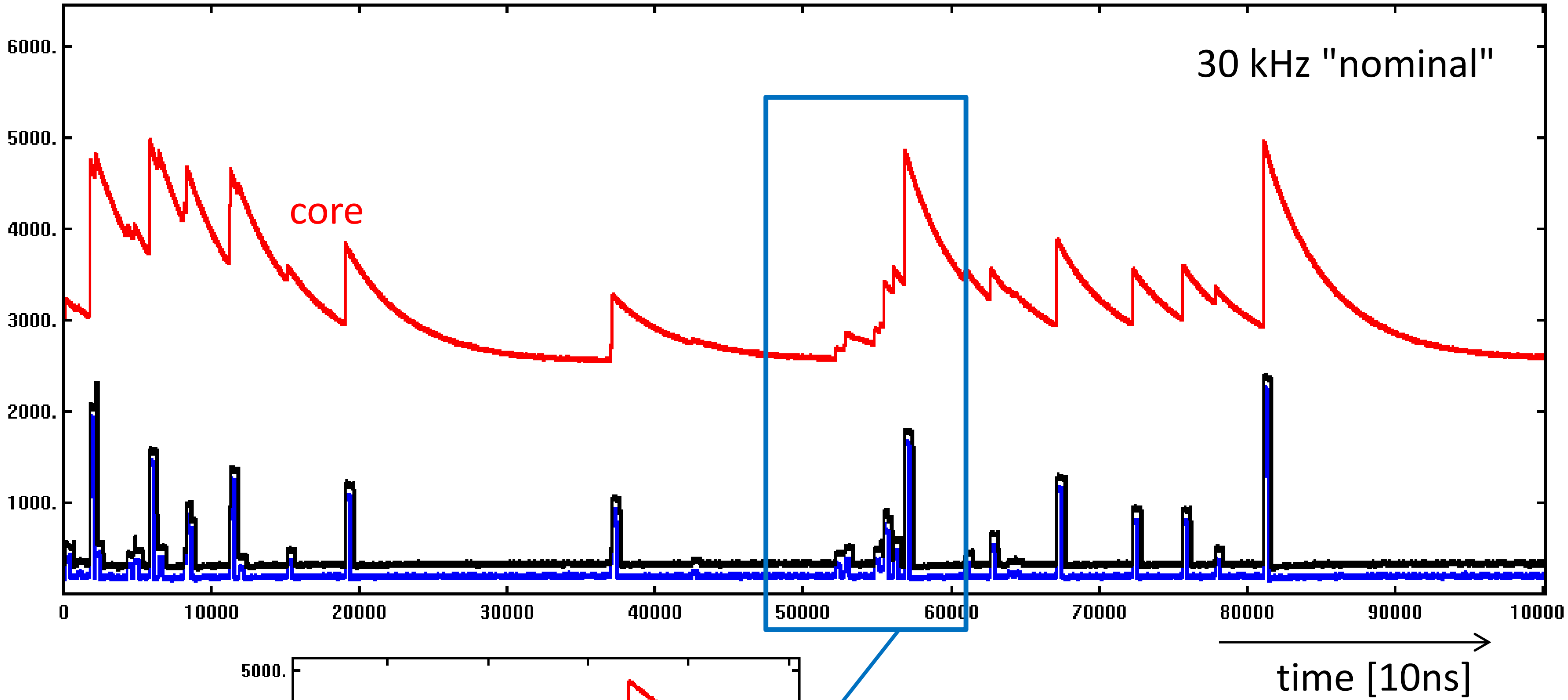
3) $$V_{out}[i] = V_{av2}[i] - V_{av1}[i]$$

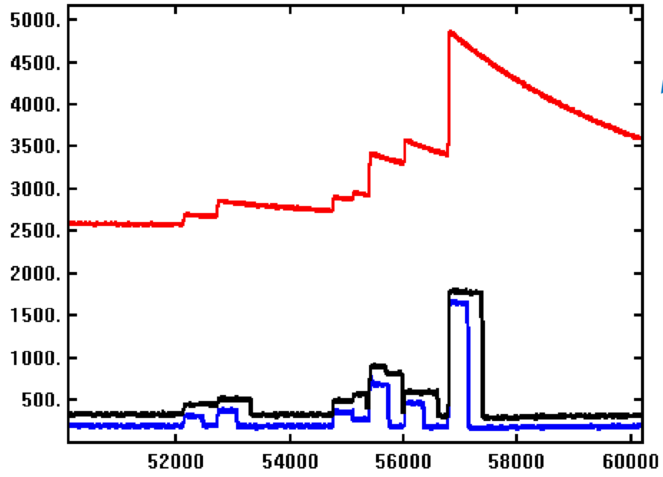
Signal amplitude =
value at the top –
value of the baseline

Signal processing at high counting rates



Signal processing at high counting rates

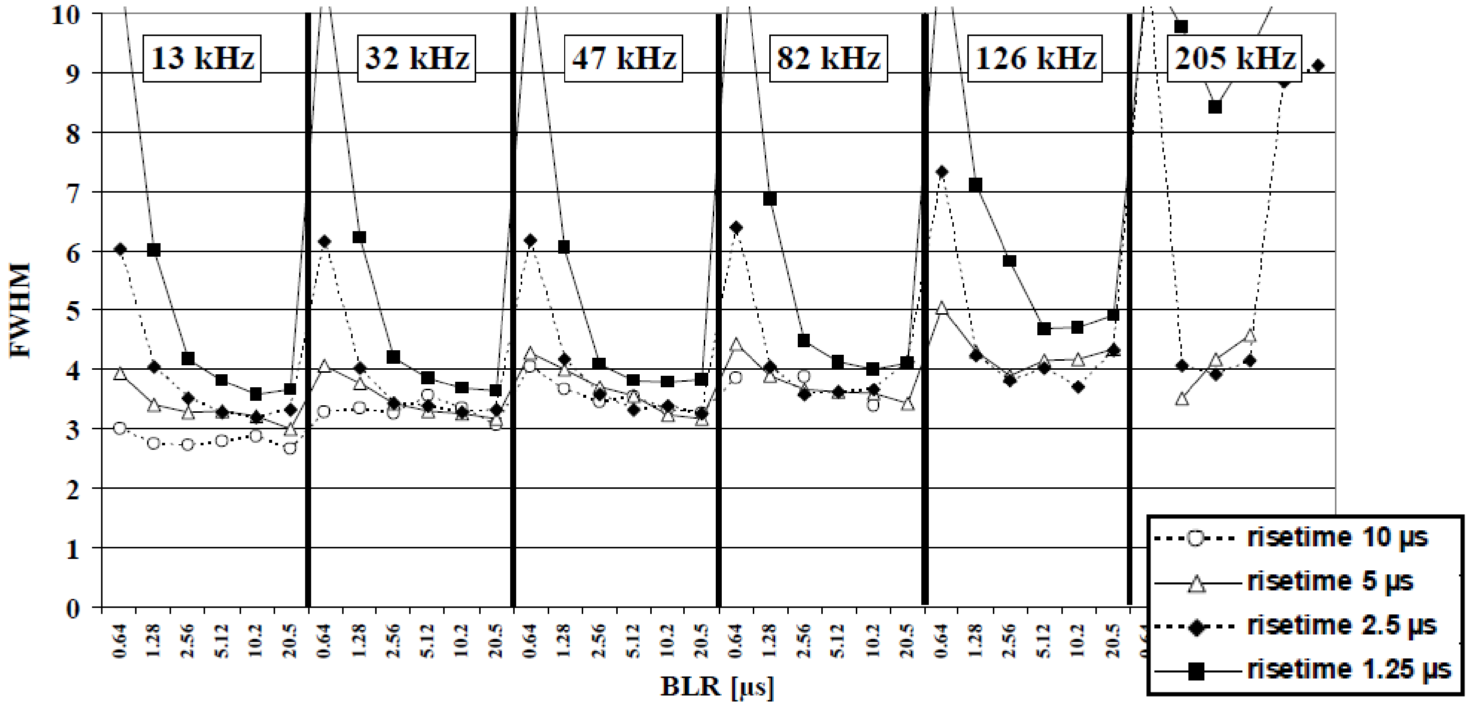




MWD amplitude:
risetime 5us
risetime 2.5us

Singles rates and shaping time

6 different rates x 4 trapezoid risetimes x 6 BLR lengths



F. Recchia

Singles rates and shaping time

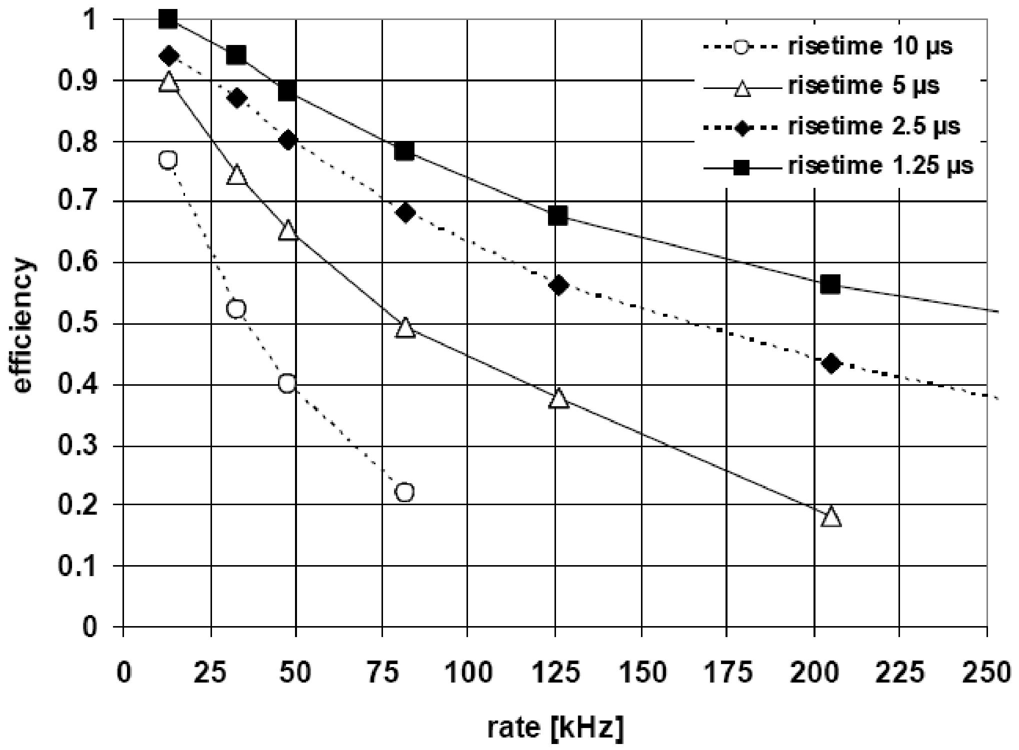
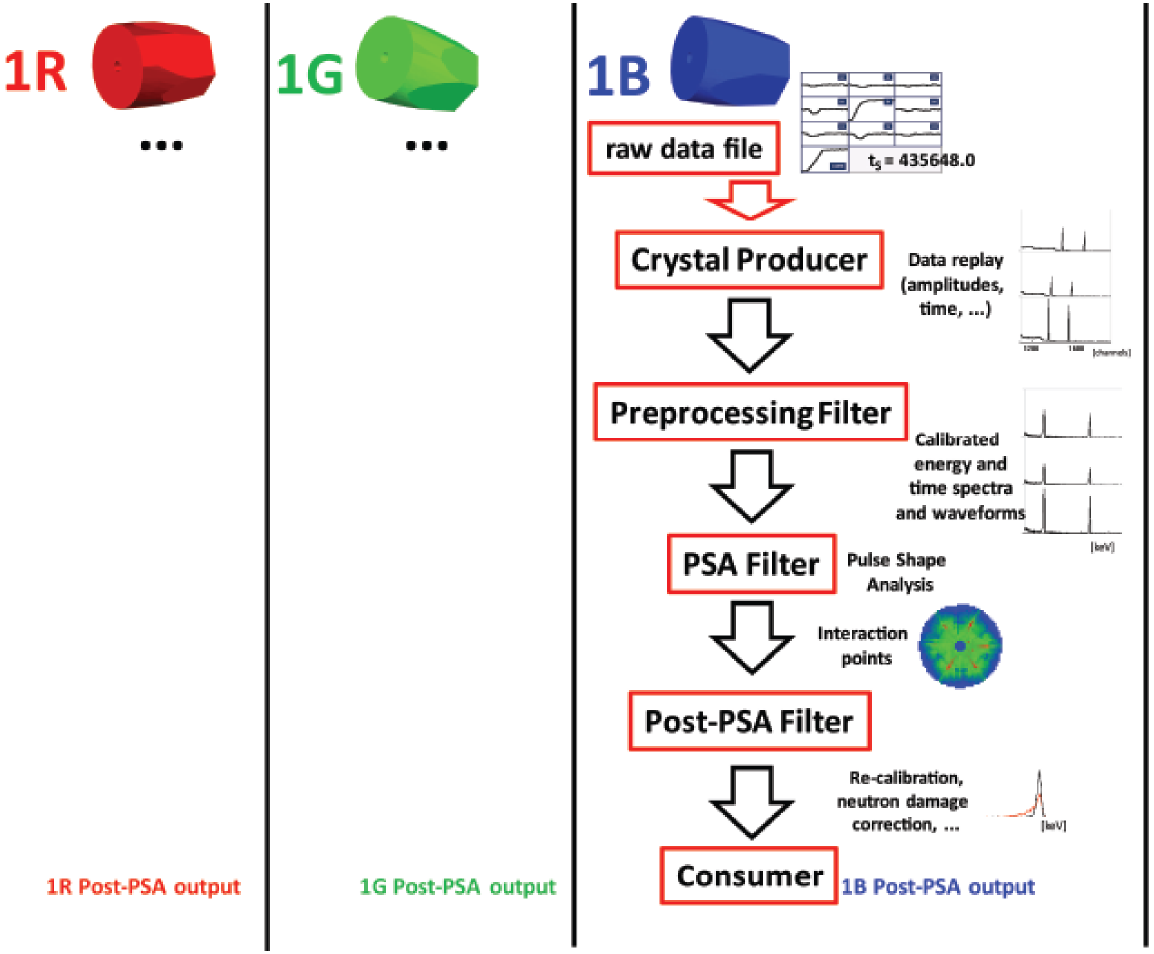


Fig. 1. Efficiency as a function of rate.

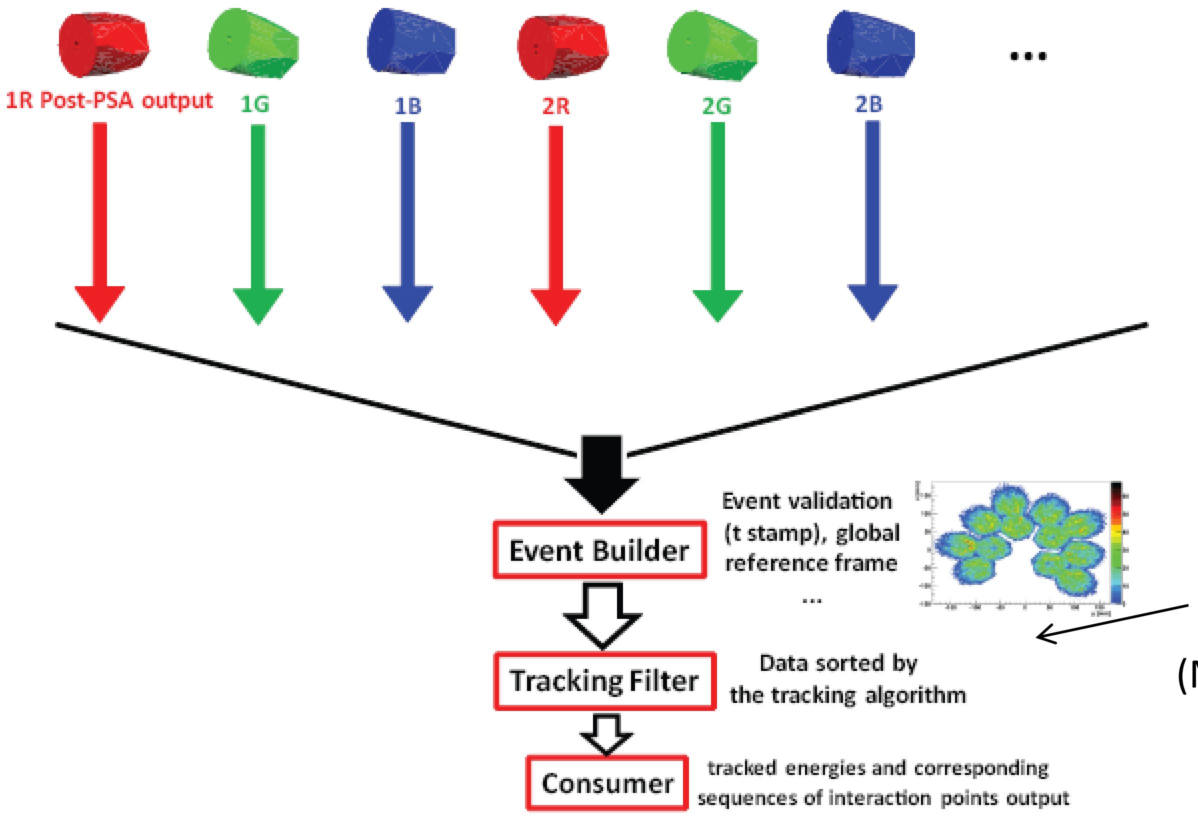
Structure of Data Processing

Local Level Processing




```
Chain 4 1B/
Producer CrystalProducerATCA
Filter PreprocessingFilterPSA
Filter PSAFilterGridSearch
Consumer BasicAFC
```

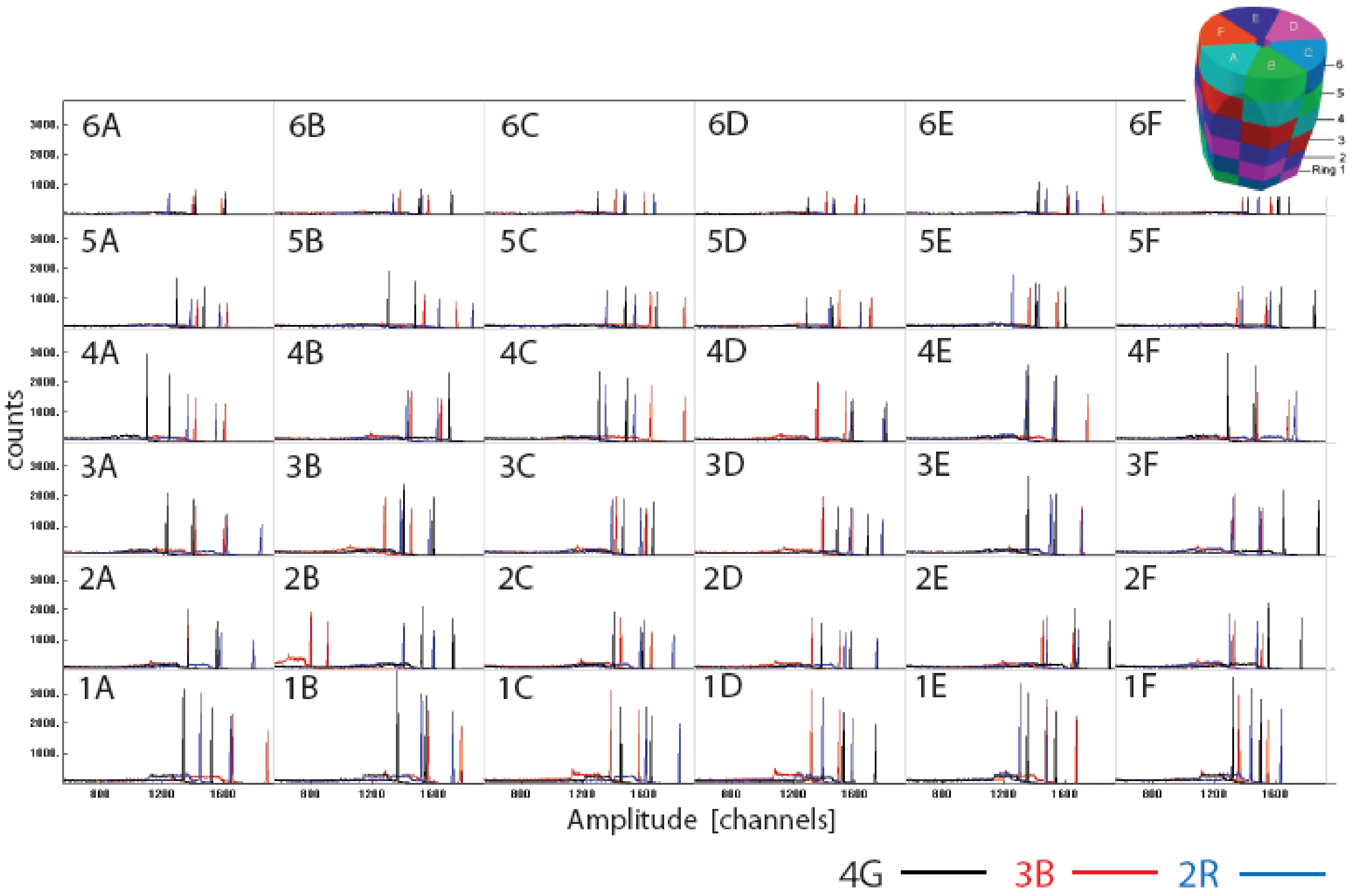
Structure of Data Processing
Global Level Processing



Ancillary Producer/Filter

(Merger)

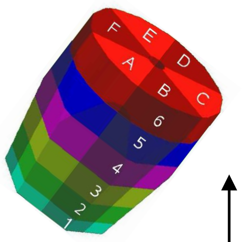
Data preparation to the PSA: energy calibrations

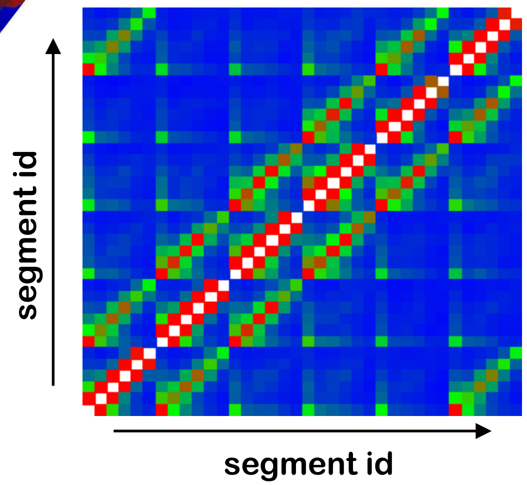


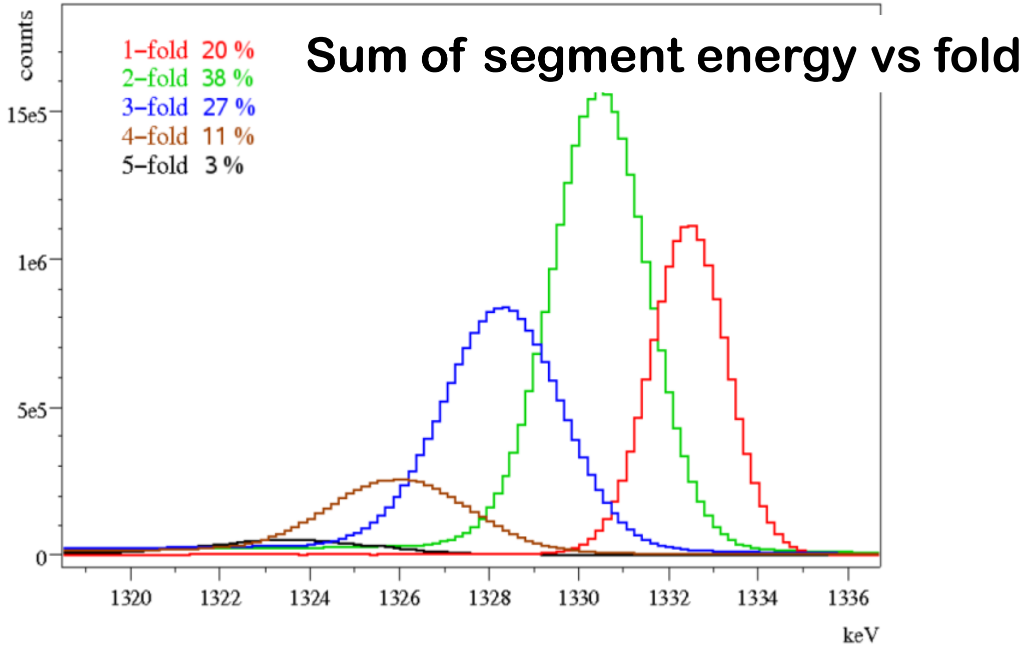
Calibration of traces: from calibrations of amplitudes and MWD parameters

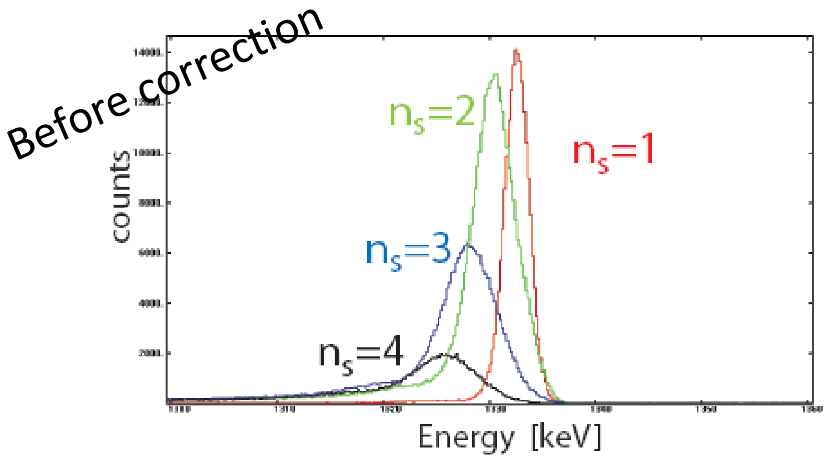
Data preparation to the PSA: cross-talk correction

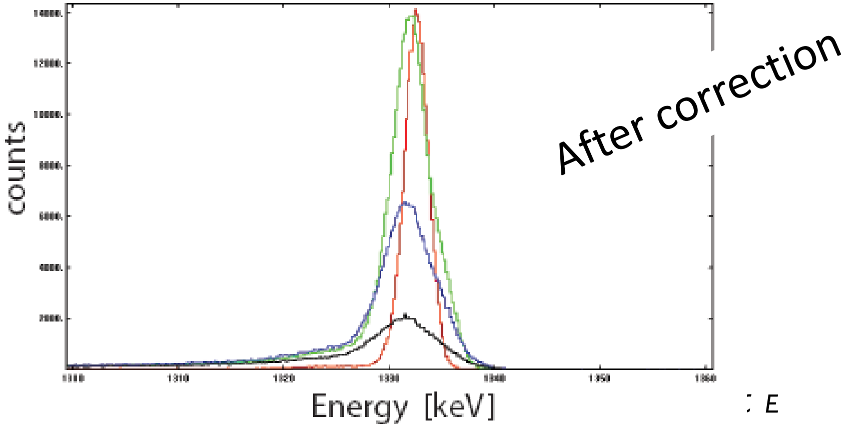
Generate strong energy shifts proportional to the segment fold



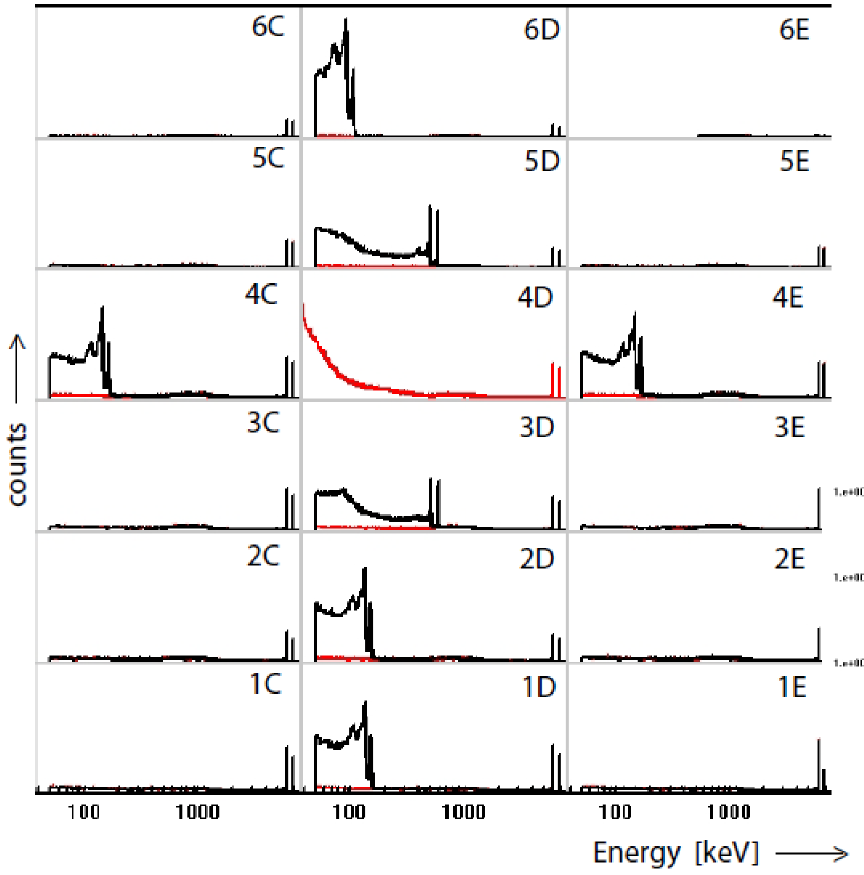


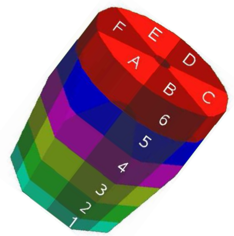


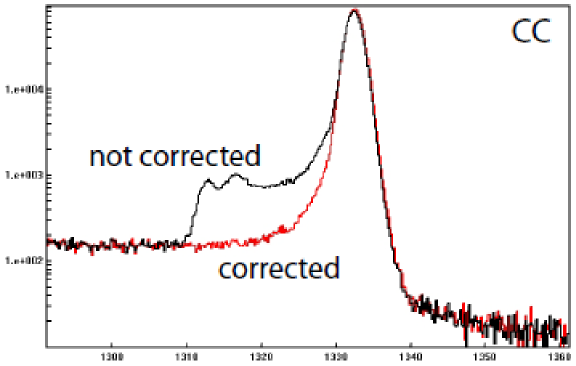




Data preparation to the PSA: recovery of missing segment

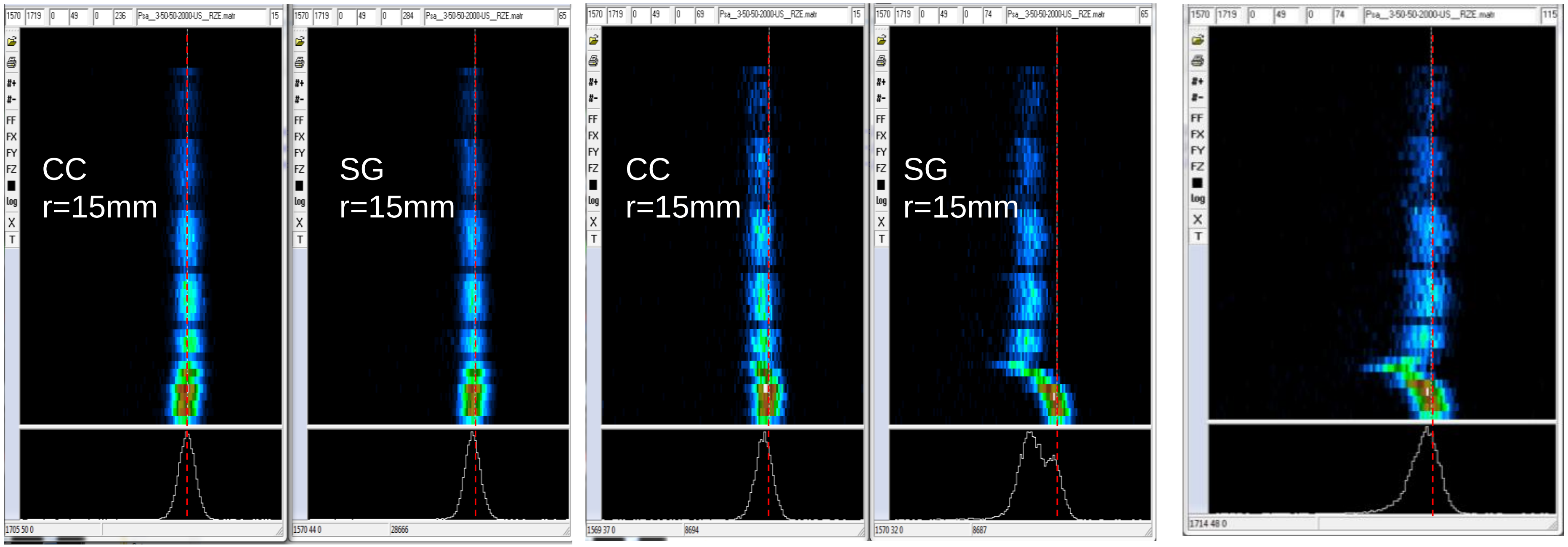


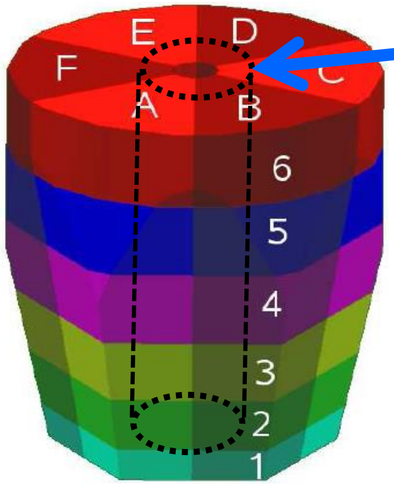




Neutron-damage correction

April 2010 | **July 2010** | **→ corrected**





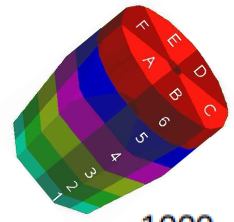
The 1332 keV peak as a function of crystal depth (z) for interactions at r = 15mm

Charge loss due to neutron damage → proportional to the path length to the electrodes

Use PSA interaction points and modeling of charge trapping to correct the effect

B.Bruyneel et al, Eur. Phys. J. A 49 (2013) 61

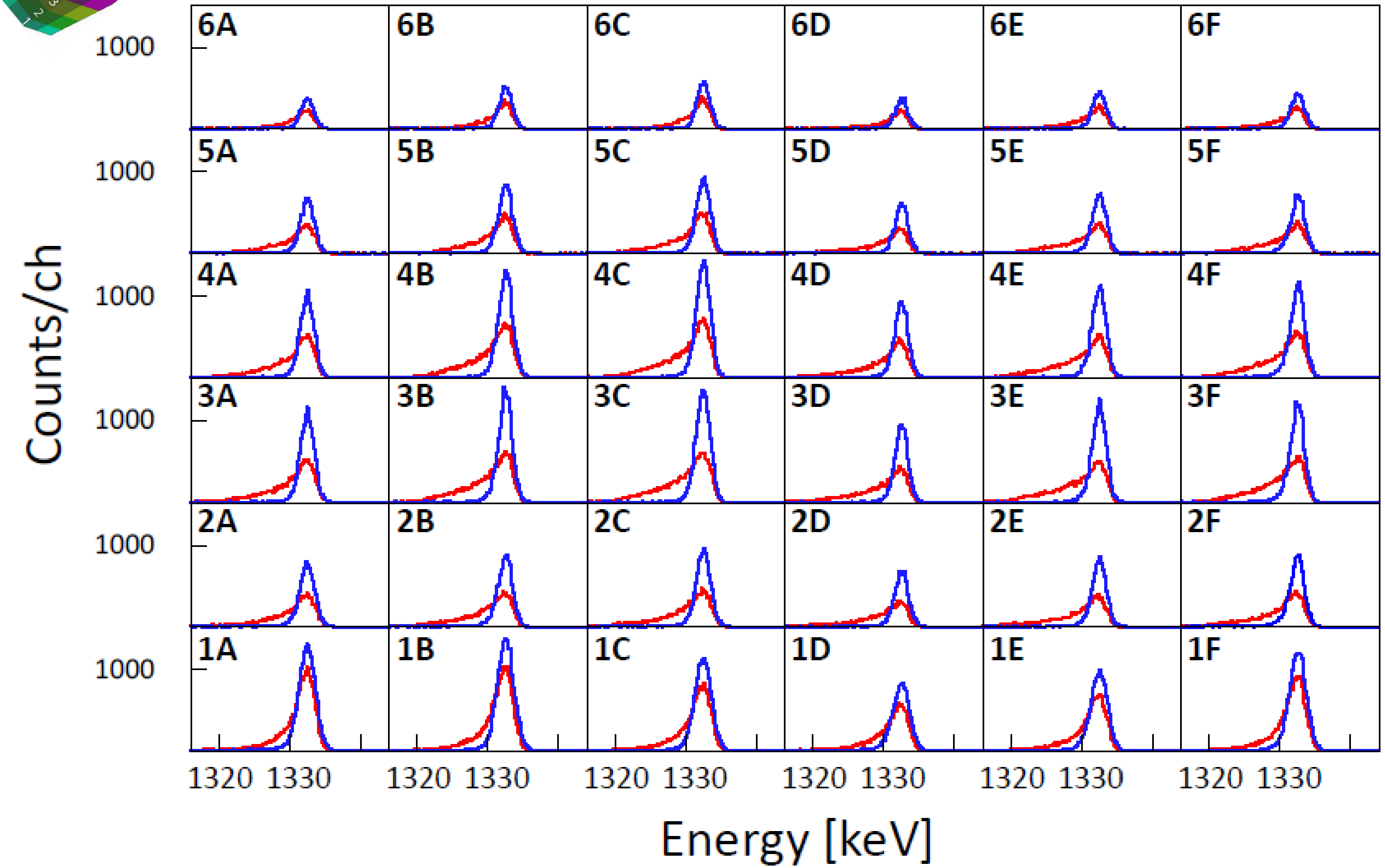
Effect of the correction on energy resolution



corrected

uncorrected

Sum of segments: 5.9 keV ➔ 2.9 keV



NEUTRONS FOR SOCIETY

The nucleus is always full of surprises

Instrumentation advances ⇔ New Science