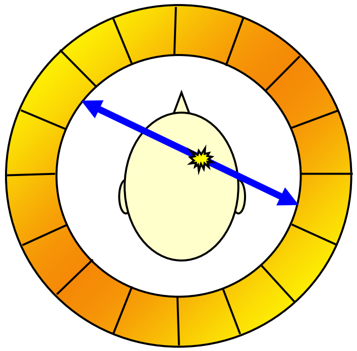
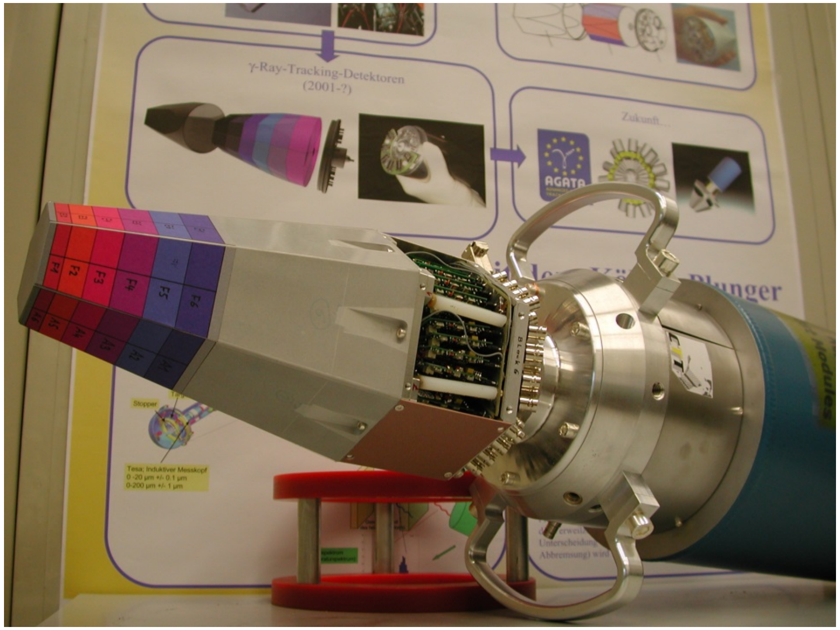
Applying γ-imaging techniques to nuclear physics experiments

Hans-Jürgen Wollersheim

- Why position sensitive γ-ray detectors for radioactive ion beams?
- 3D position sensitive HPGe detectors
- Characterization of position sensitive HPGe detectors

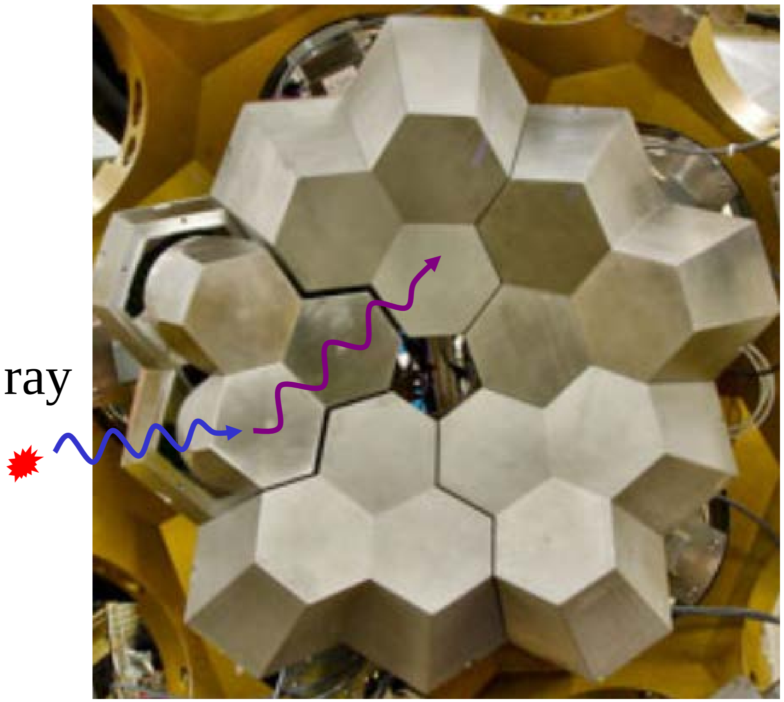




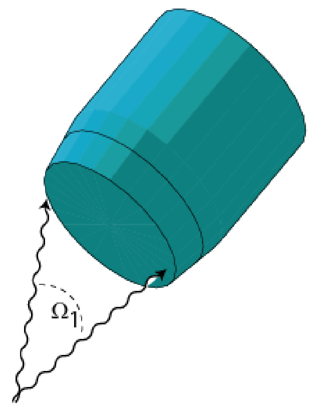
Challenges of γ-ray spectroscopy

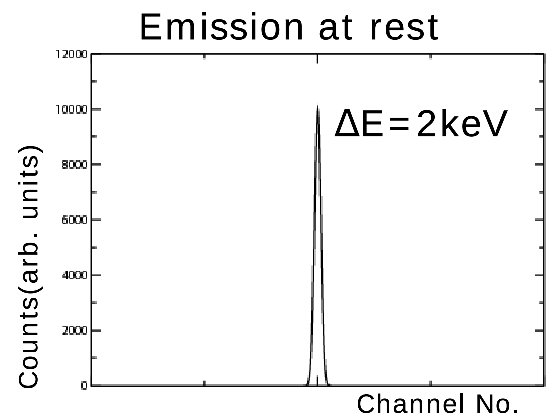
efficiency vs resolution

γ ray



Composite HPGe detectors
in ADD BACK mode

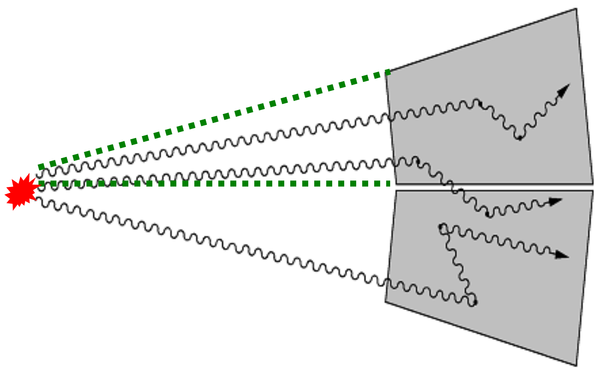


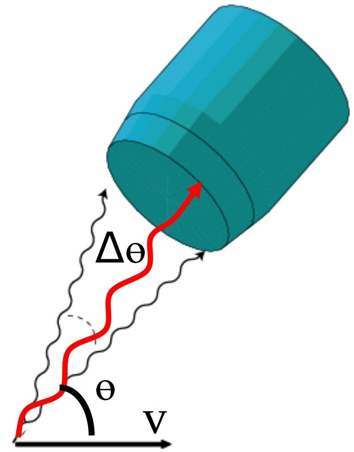


Challenges of γ-ray spectroscopy

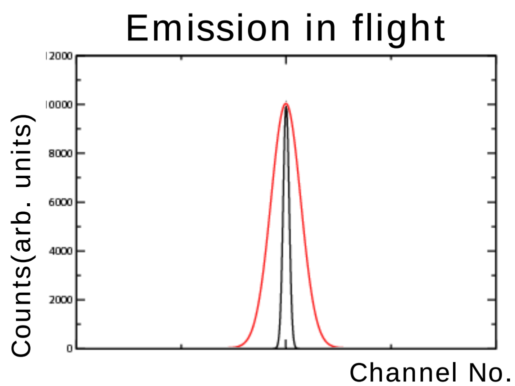
efficiency vs resolution

High M_γ



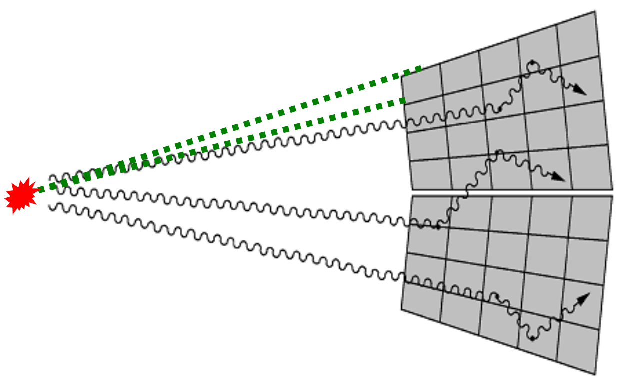


Doppler broadening



$$\left(\frac{\Delta E_{\gamma 0}}{E_{\gamma 0}}\right)^2 = \left(\frac{\beta \cdot \sin \vartheta_\gamma}{1-\beta \cdot \cos \vartheta_\gamma}\right)^2 \cdot \left(\Delta \vartheta_\gamma\right)^2$$

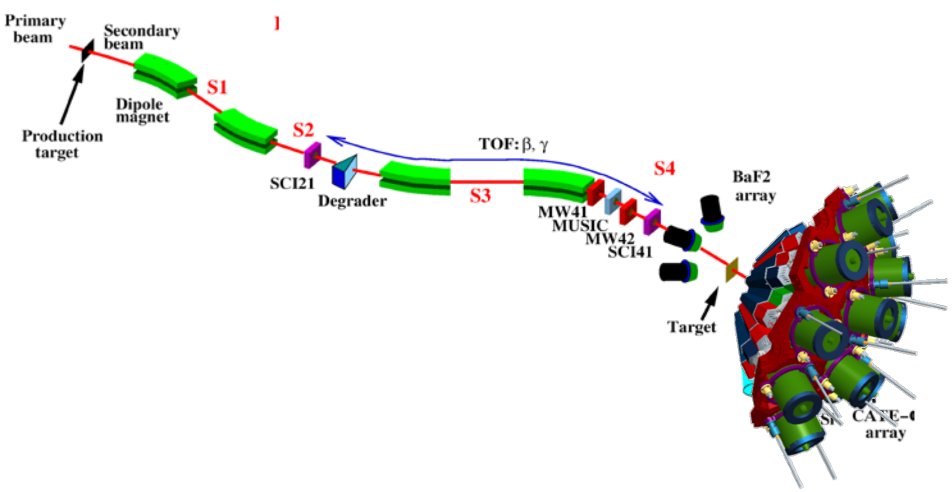
Solution

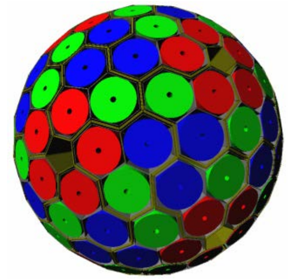


- Segmentation
- Gamma-ray tracking
- Pulse shape analysis
- Doppler correction

γ-ray spectroscopy with 3D position sensitive HPGe detectors

In flight γ-ray spectroscopy → HISPEC





Advanced
GAmma
Tracking
Array

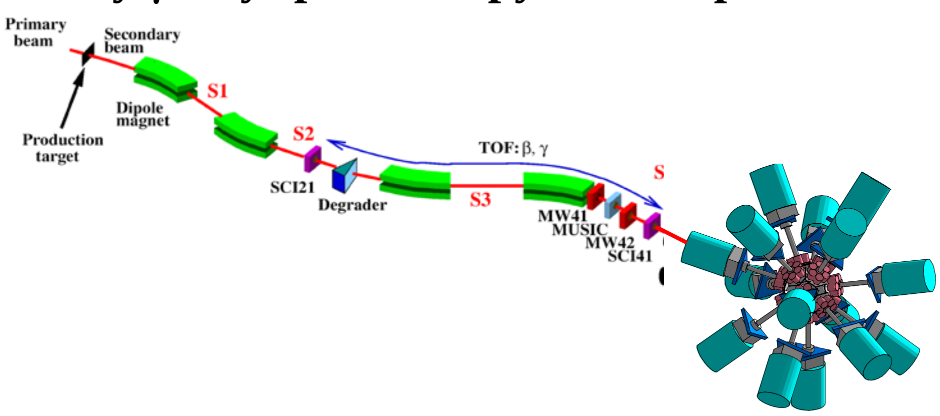
Efficiency: 43% (M_γ =1) 28% (M_γ =30)

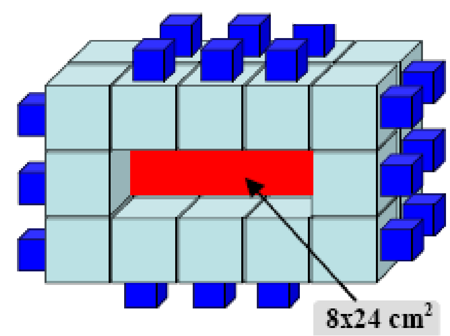
P/T: 58% (M_γ=1) 49% (M_γ=30)

Angular resolution: ~1^o

FWHM (1 MeV, v/c=50%) ~ 6 keV

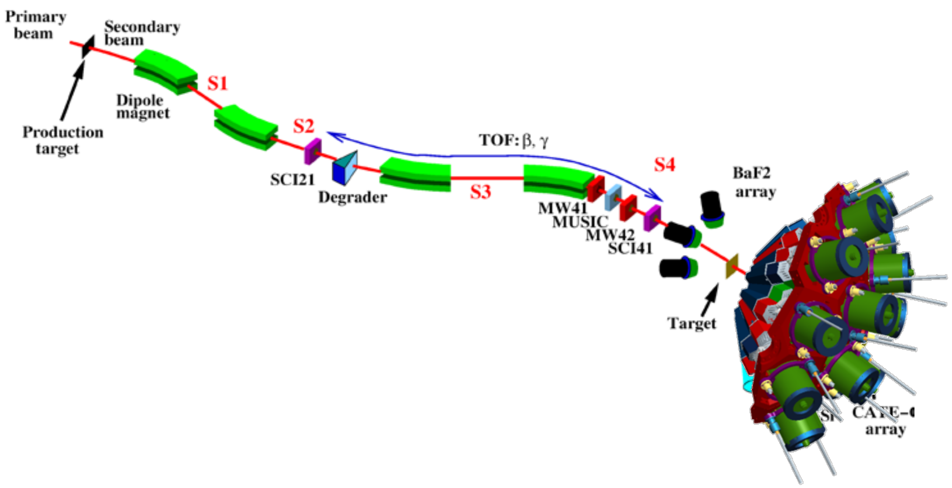
Decay γ–ray spectroscopy after implantation → DESPEC

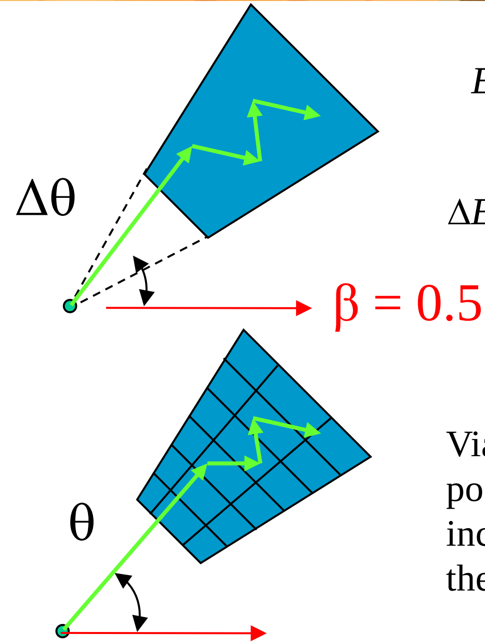




γ-ray spectroscopy with 3D position sensitive HPGe detectors

In flight γ-ray spectroscopy



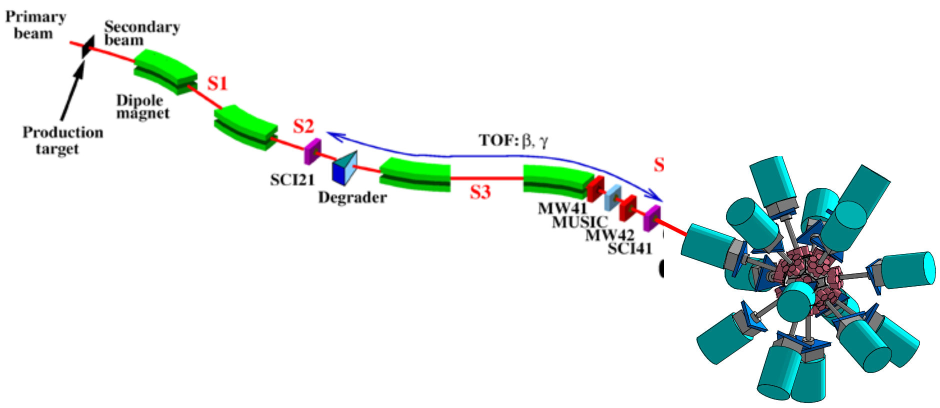


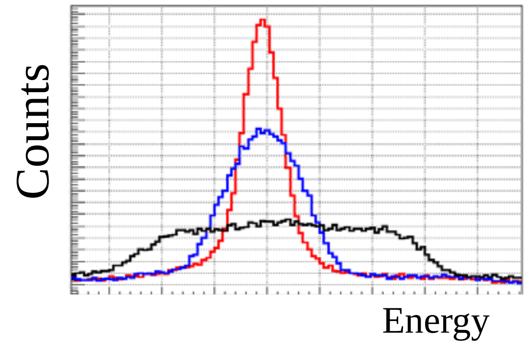
$$E_\gamma = E_\gamma^0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$

$$\Delta E_\gamma = E_\gamma^0\, \beta \sin\theta\, \Delta\theta$$

Via *tracking* it becomes possible to determine the incident angle and preserve the good energy resolution.

Decay γ–ray spectroscopy after implantation





E_γ = 1.3 MeV

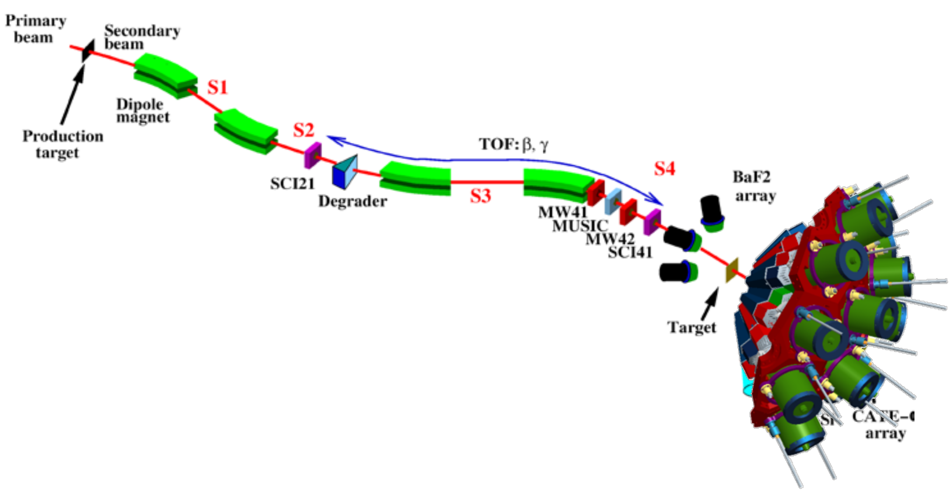
PSA = 5 keV

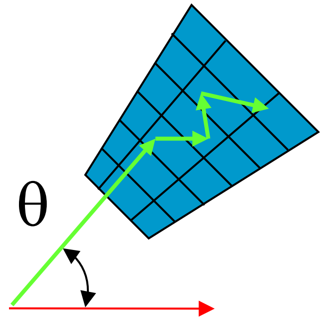
Segment = 12 keV

Detector = 35 keV

γ-ray spectroscopy with 3D position sensitive HPGe detectors

In flight γ-ray spectroscopy





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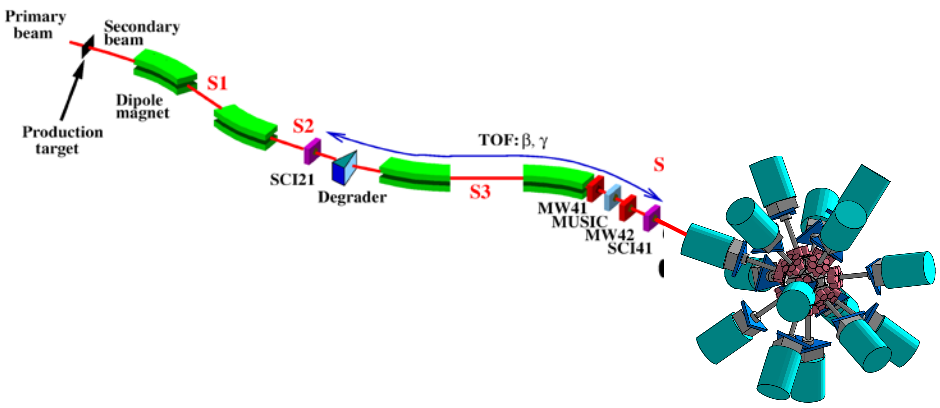
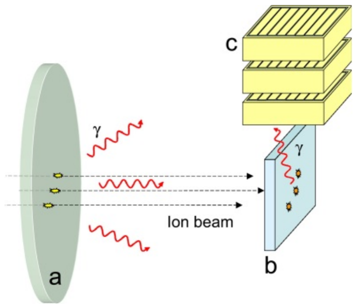
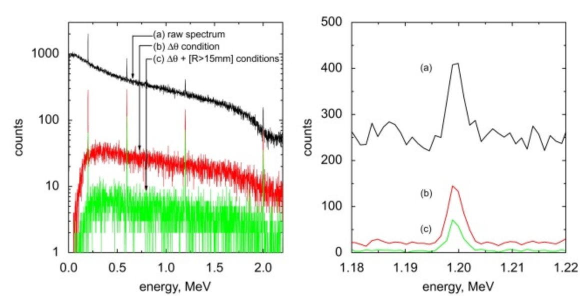


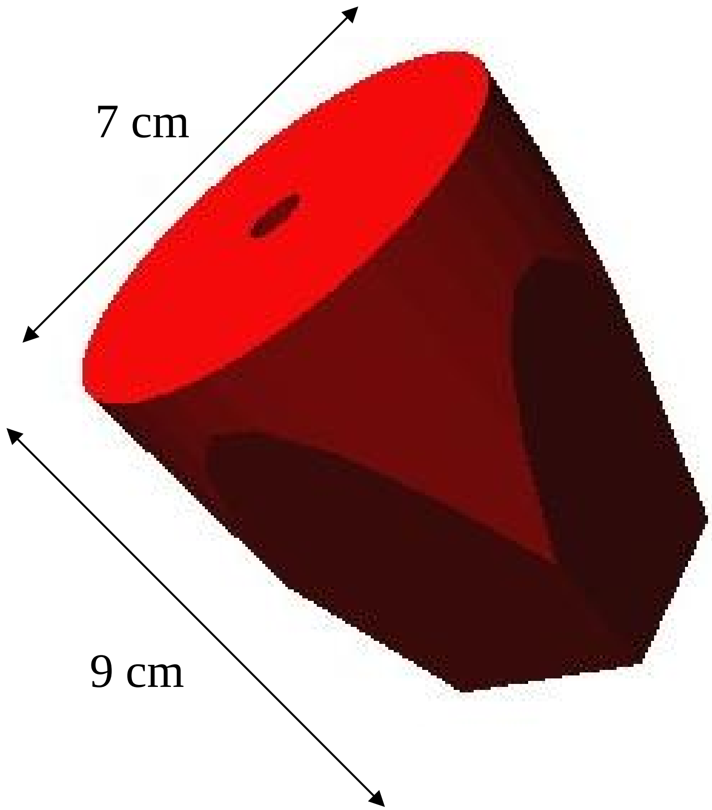


Background suppression and P/T can be improved by applying imaging techniques.



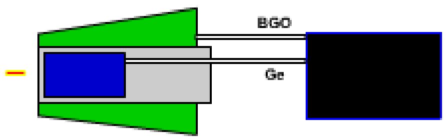
S. Tashenov, et al. NIMA 586 (2008) 224-228

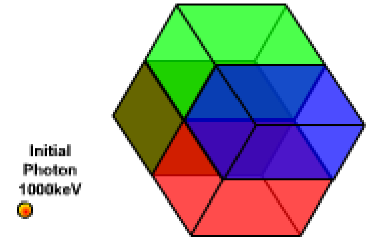
HPGe detector

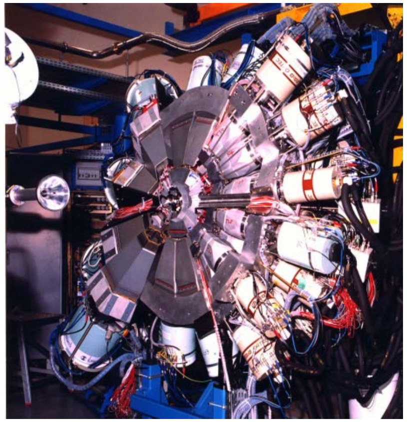


Gamma Arrays based on Compton Suppressed Spectrometers

Tracking Arrays based on Position Sensitive Ge Detectors

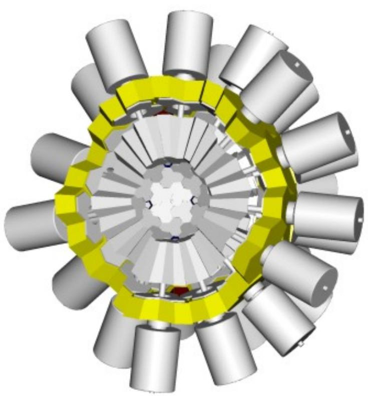




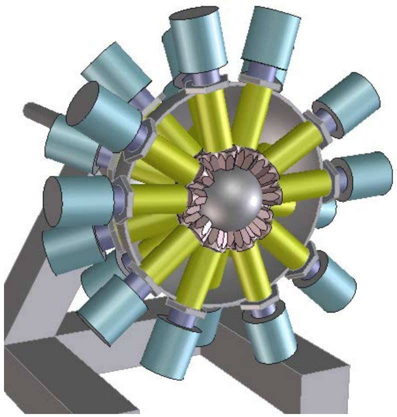


EUROBALL

GAMMASPHERE



AGATA



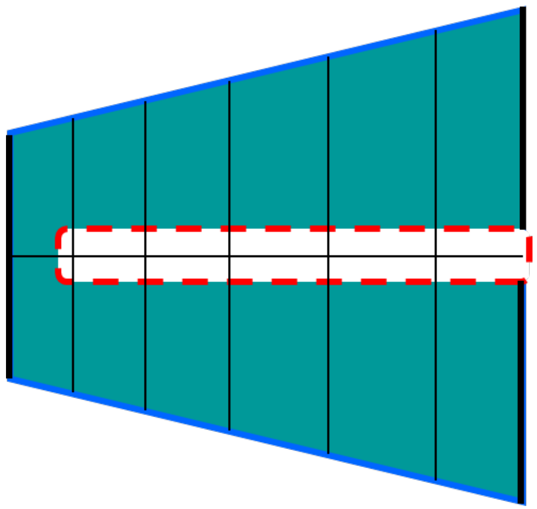
GRETA

$\varepsilon \sim 10 - 7\ \%$
$(M_\gamma = 1 - M_\gamma = 30)$

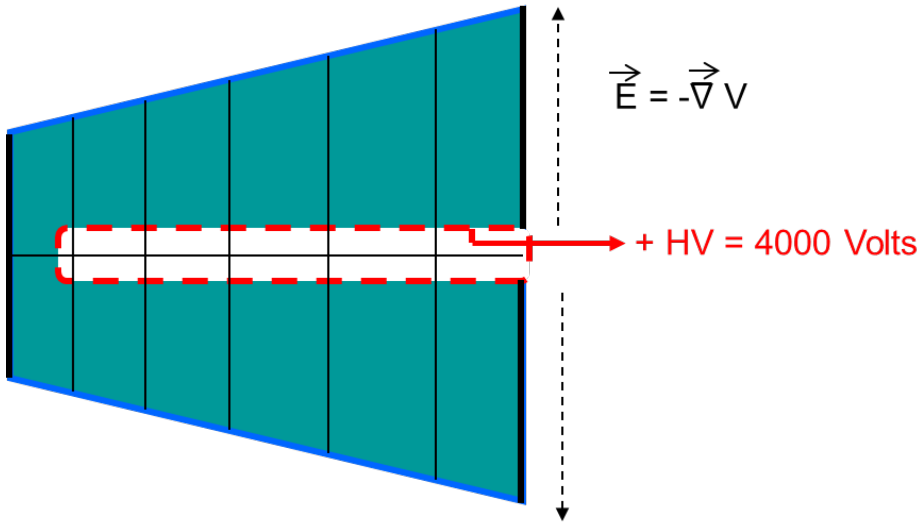
→

$\varepsilon \sim 50 - 25\ \%$
$(M_\gamma = 1 - M_\gamma = 30)$

HPGe detector: working principle



HPGe detector: working principle



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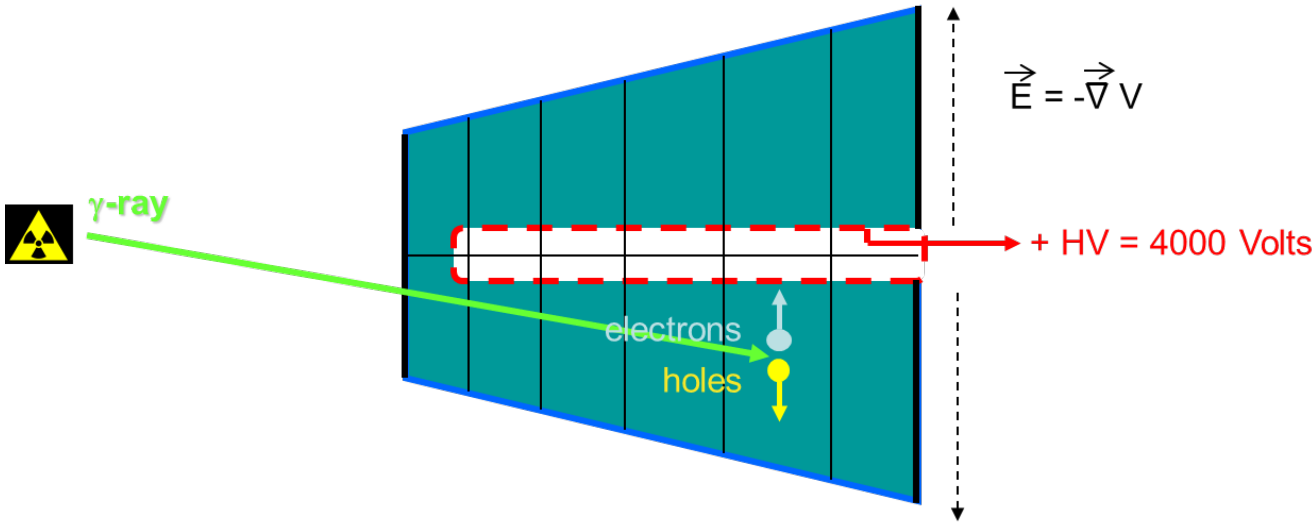

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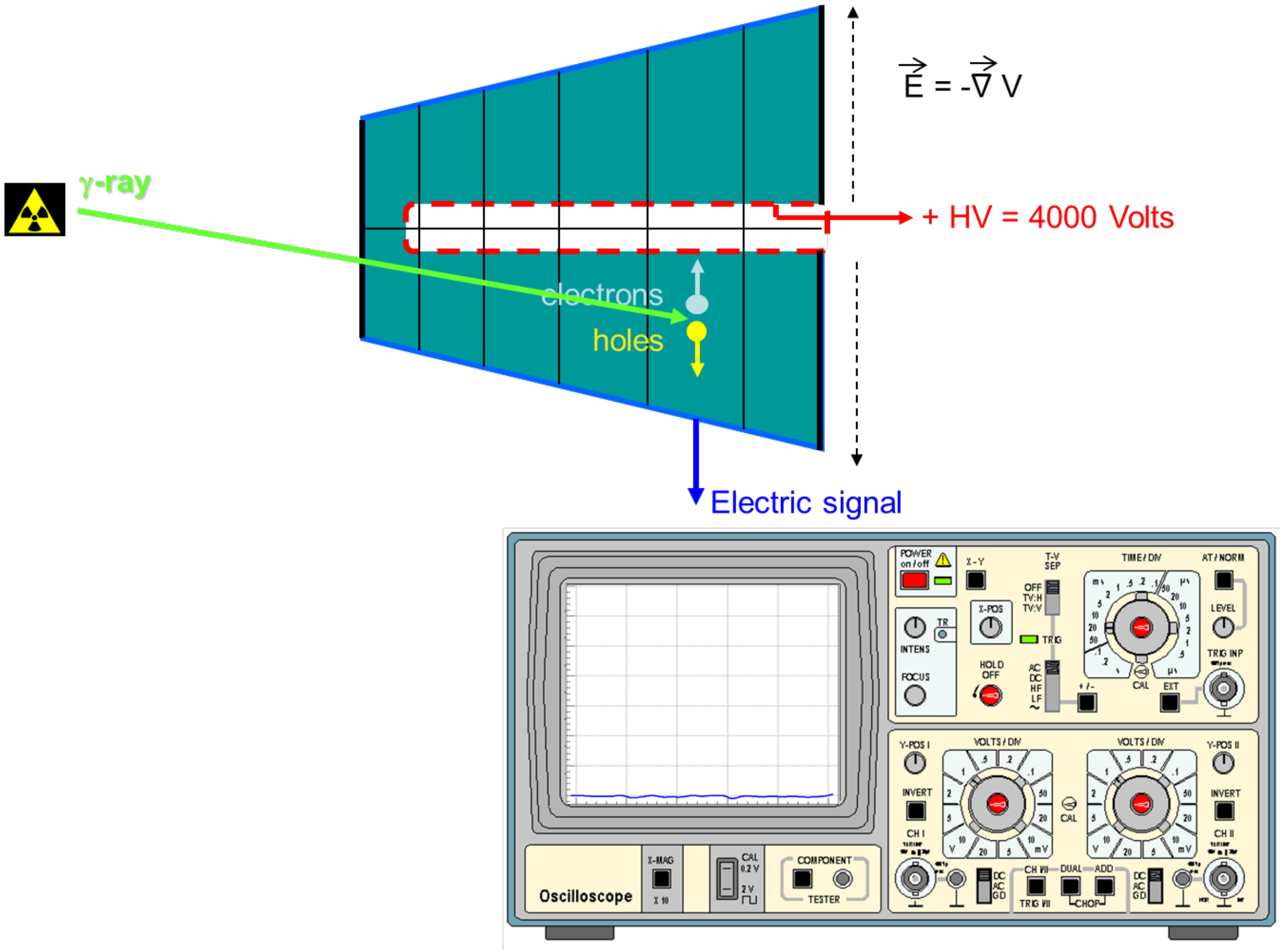

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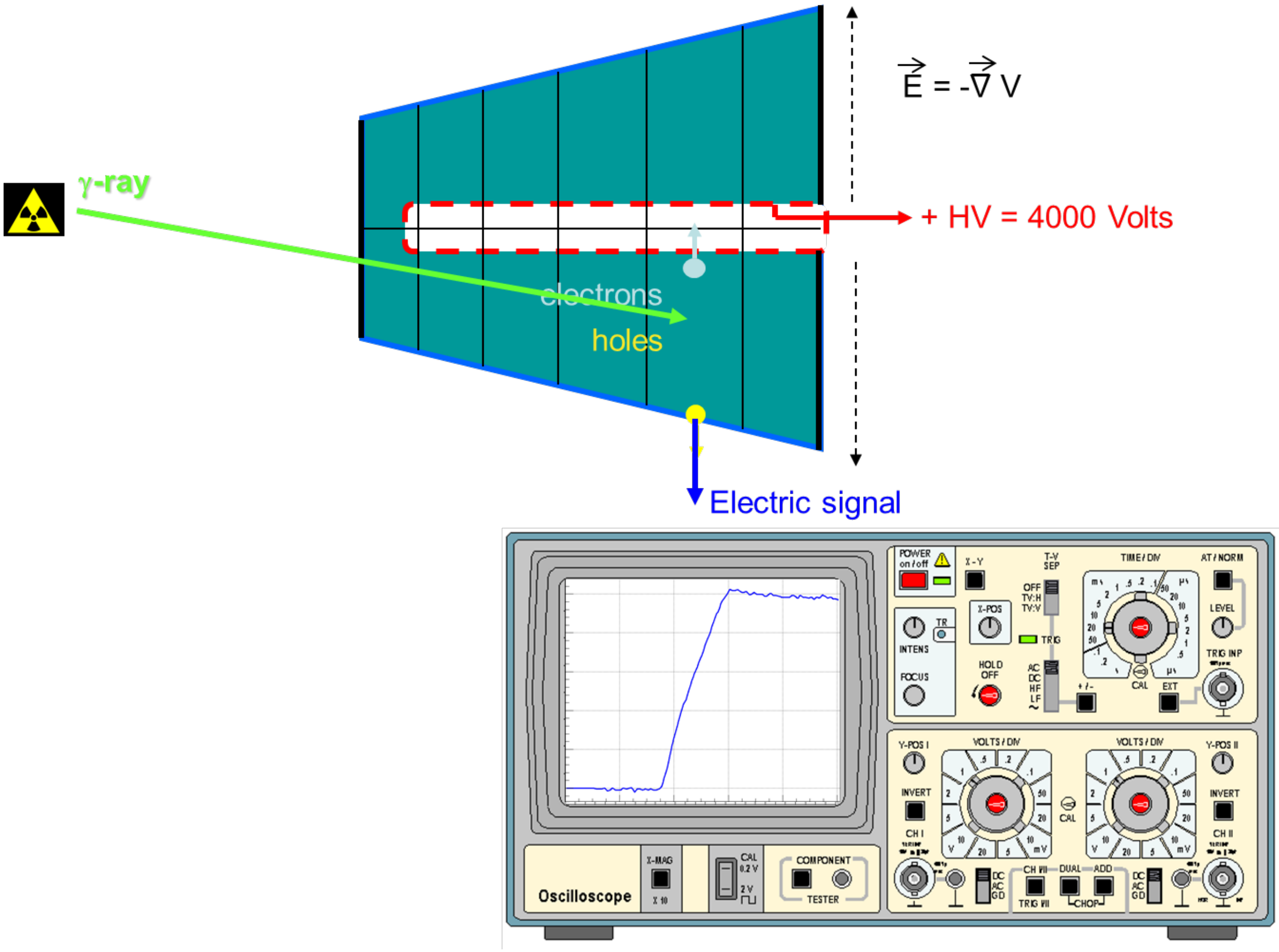
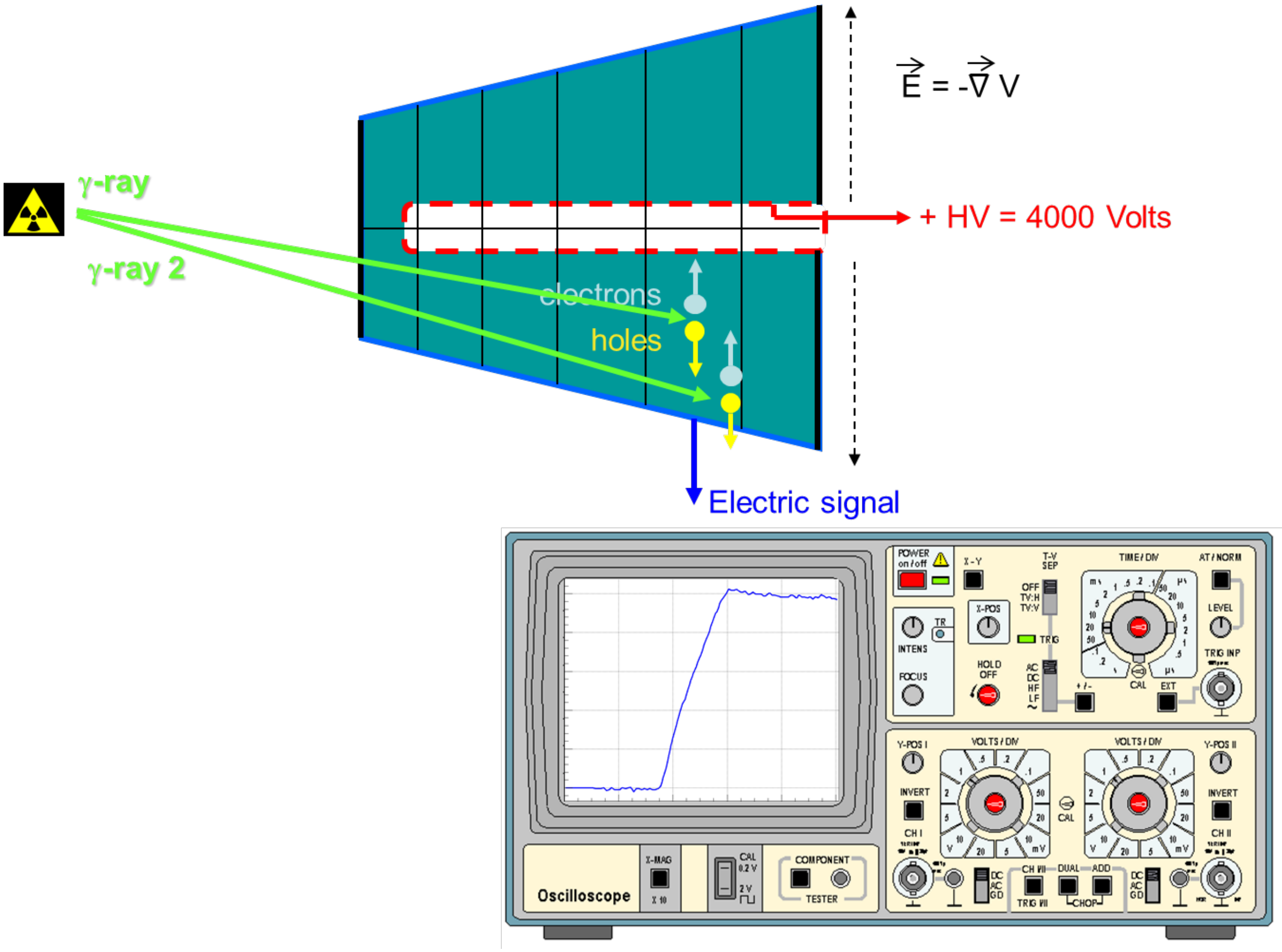
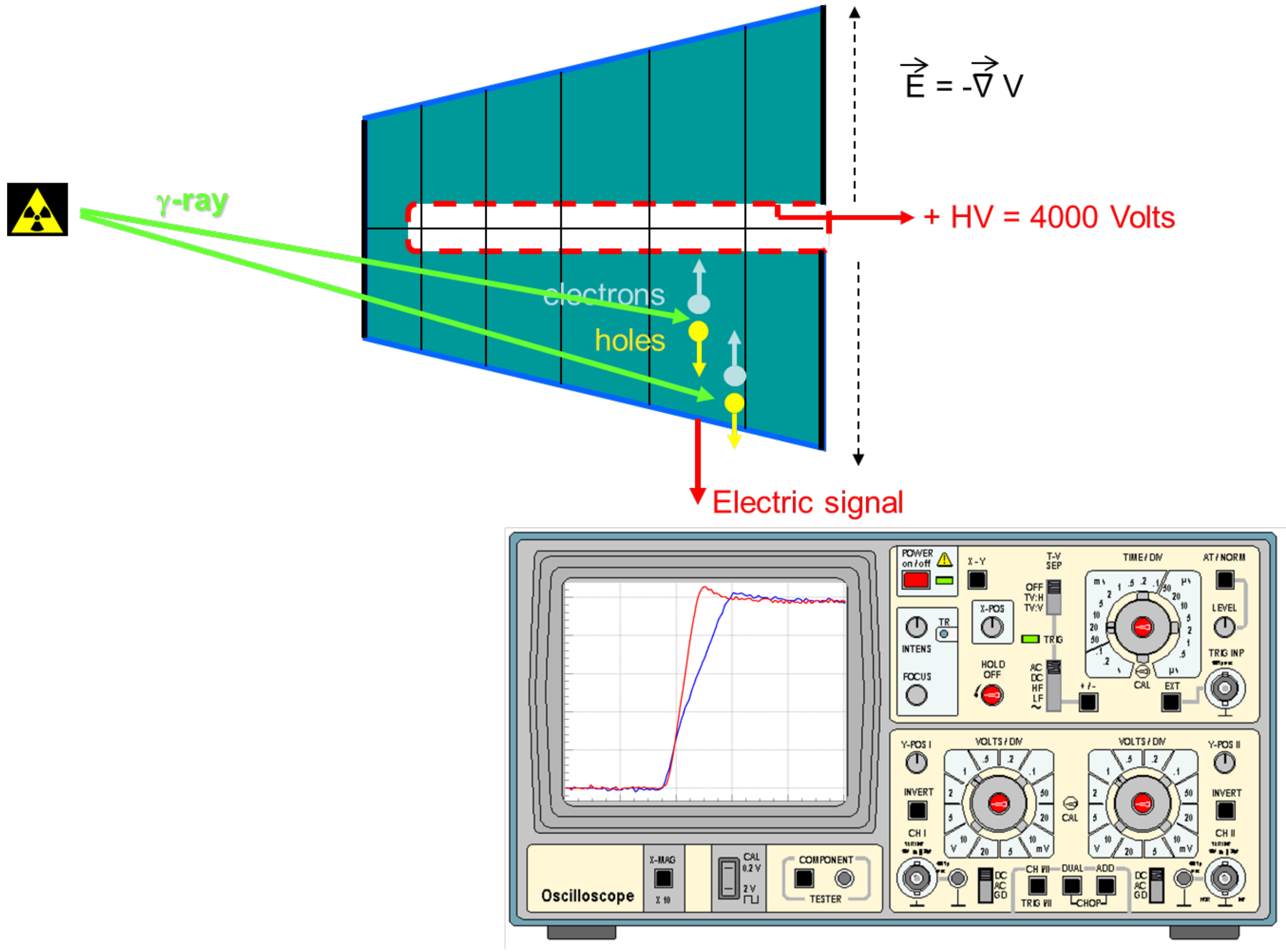


HPGe detector: position sensitivity

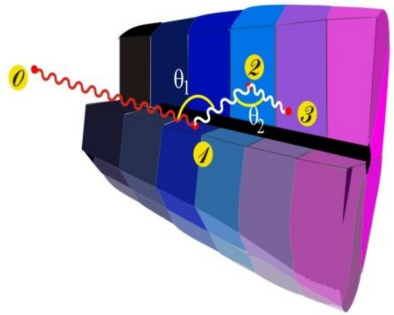


HPGe detector: position sensitivity



Ingredients of γ-ray tracking

Highly segmented HPGe detectors



AGATA:

Advanced Gamma Tracking Array

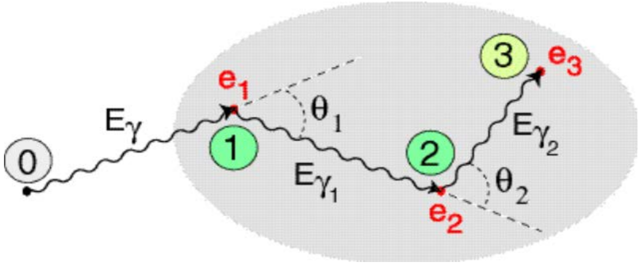
Digital electronics to record and process segment signals

Pulse Shape Analysis to identify the interaction position coordinates

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

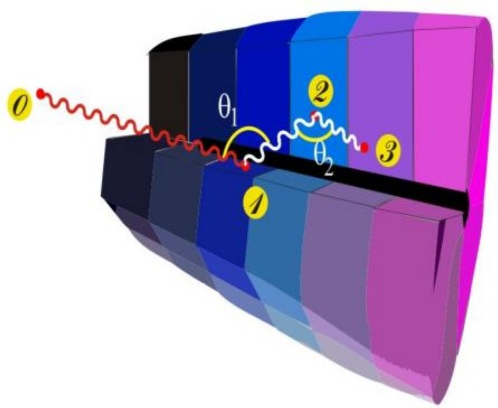
Reconstruction of tracks e.g. by evaluation of permutations of interaction points

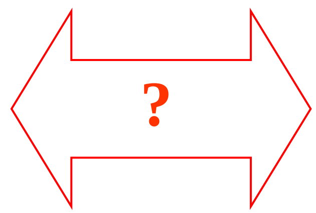
reconstructed γ-rays

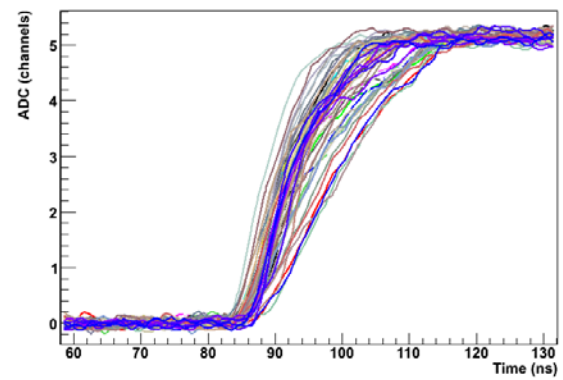


Method to characterize the pulse shape of HPGe detectors

Determine a **data-base of pulse shapes** S(x,y,z) which allows one to correlate an arbitrarily measured pulse, with an interaction position inside the detector.



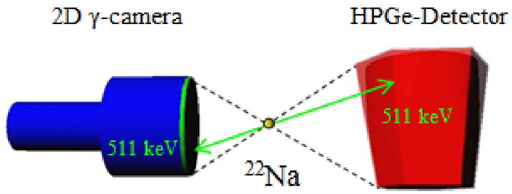




How to do this?

Using PET principle in combination with γ-ray imaging techniques !

Which γ-camera to use?



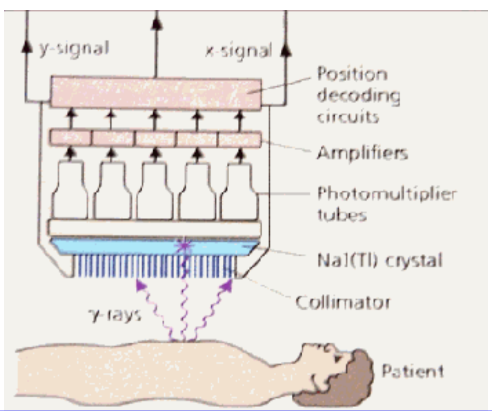
Requirements:

- Excellent resolution Δx = 2 mm
- Large field of view FoV = 8x9 cm^2

•Large FoV of about 20 cm diam.

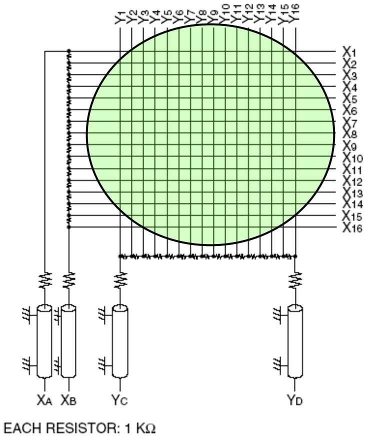
•Low Spatial Resolution 5mm-1cm

www.siemens.de



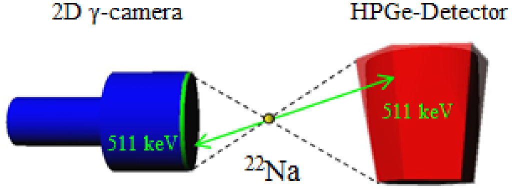
•Small FoV of about 3-4 cm diam.

•Higher Spatial Resolution 2-3mm



Gem-imaging.com

Which γ-camera to use?



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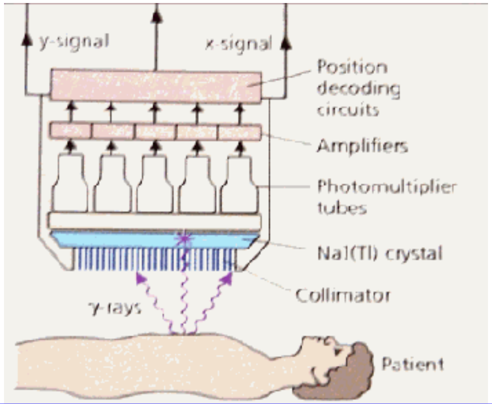

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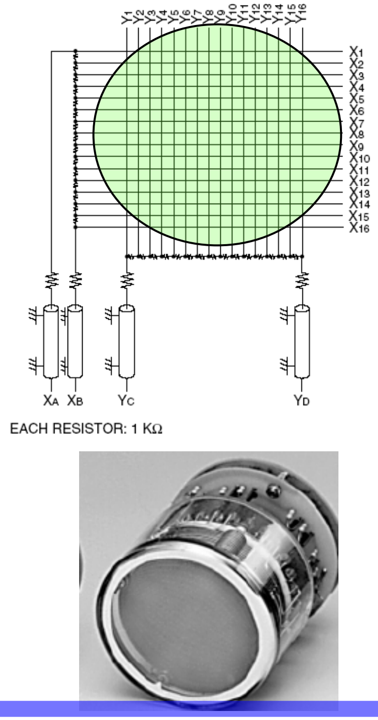

Gem-imaging.com

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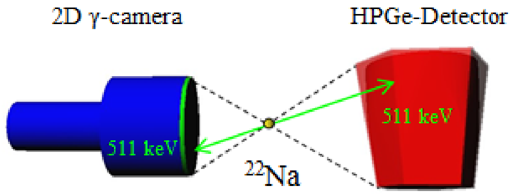

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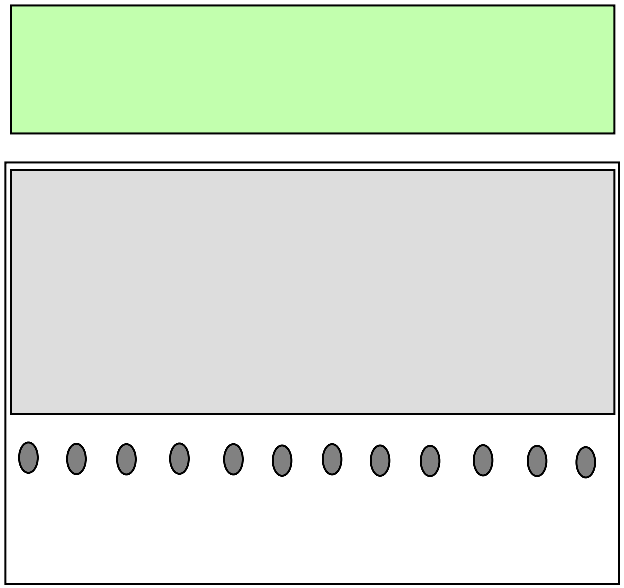
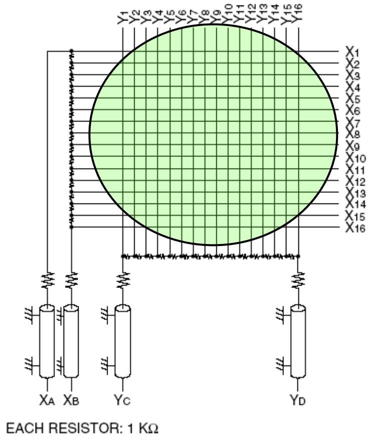


Scintillator

Position Sensitive PMT

- Small FOV of about 3-4 cm diam.
- Higher Spatial Resolution 2-3mm



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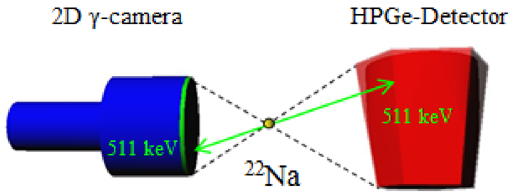

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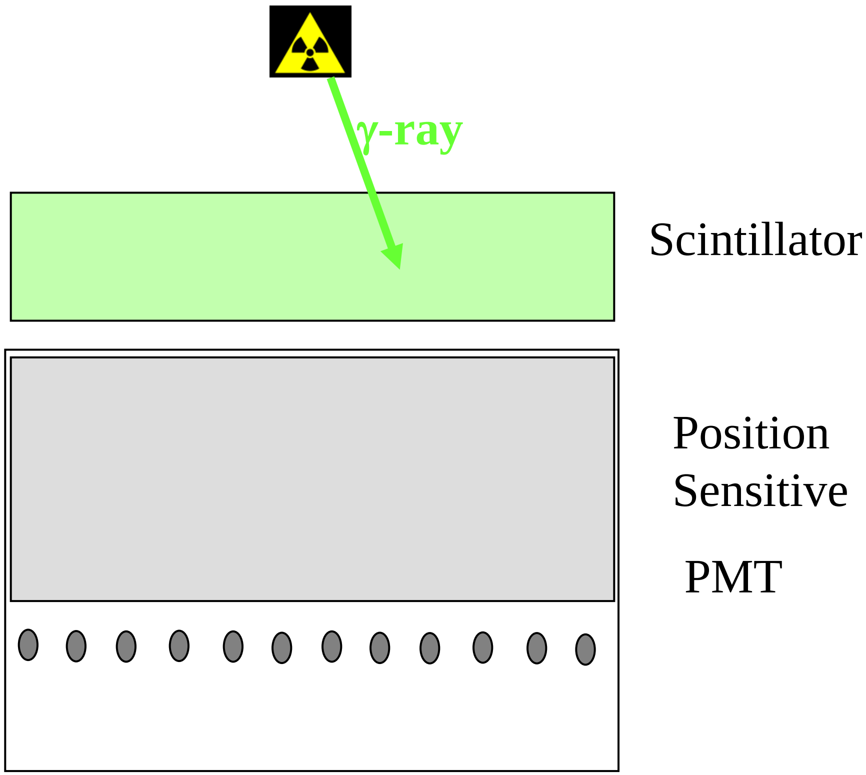

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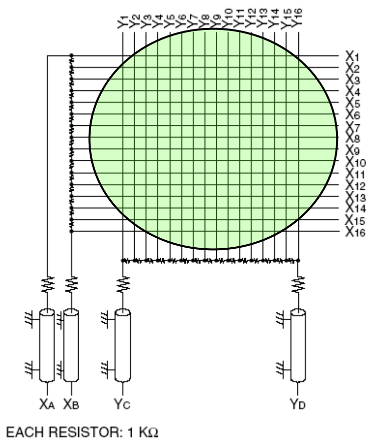

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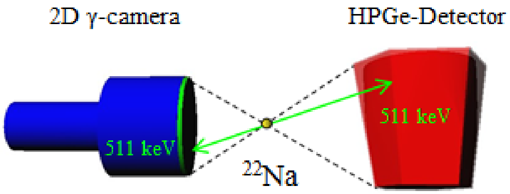

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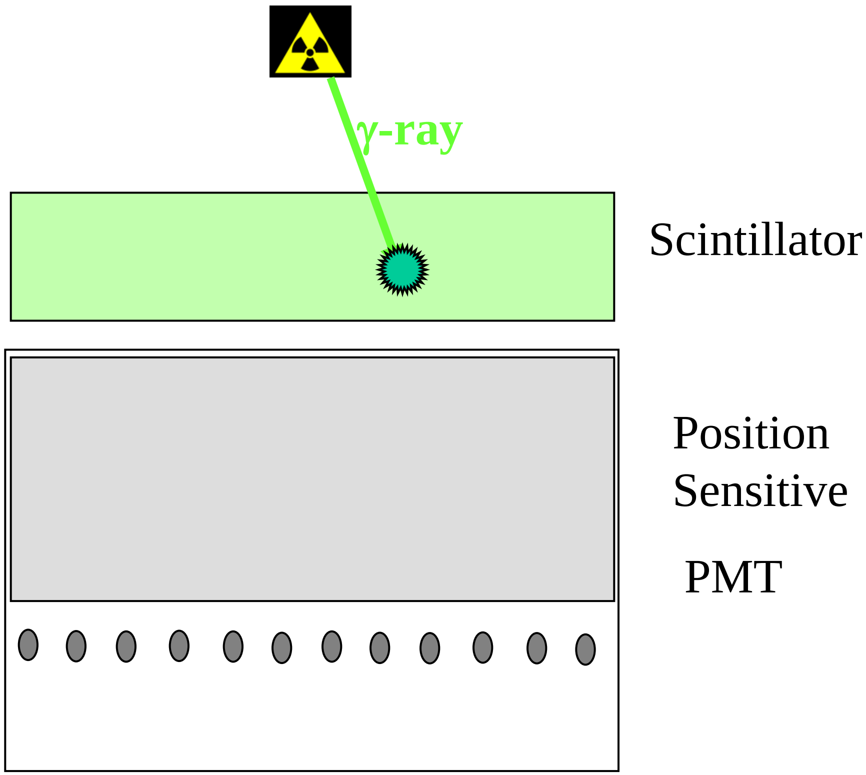

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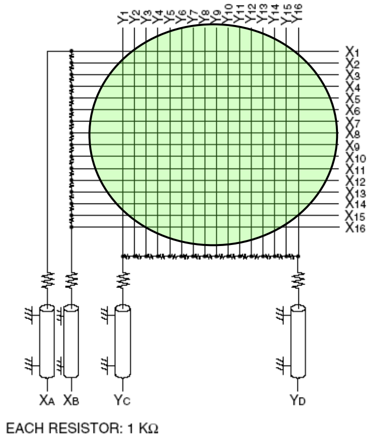

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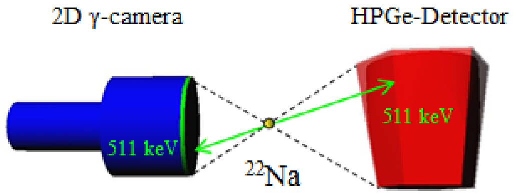

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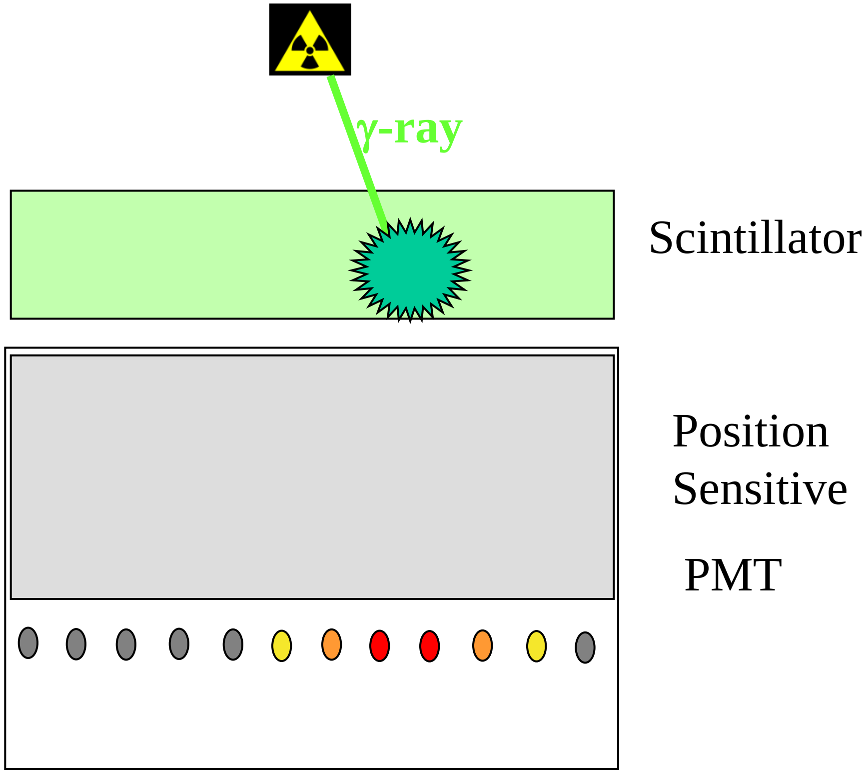

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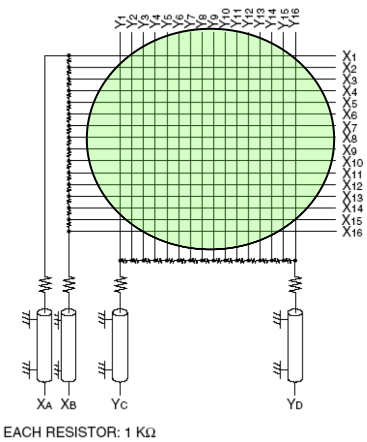

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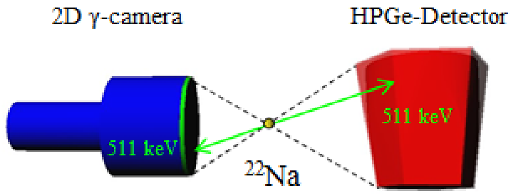

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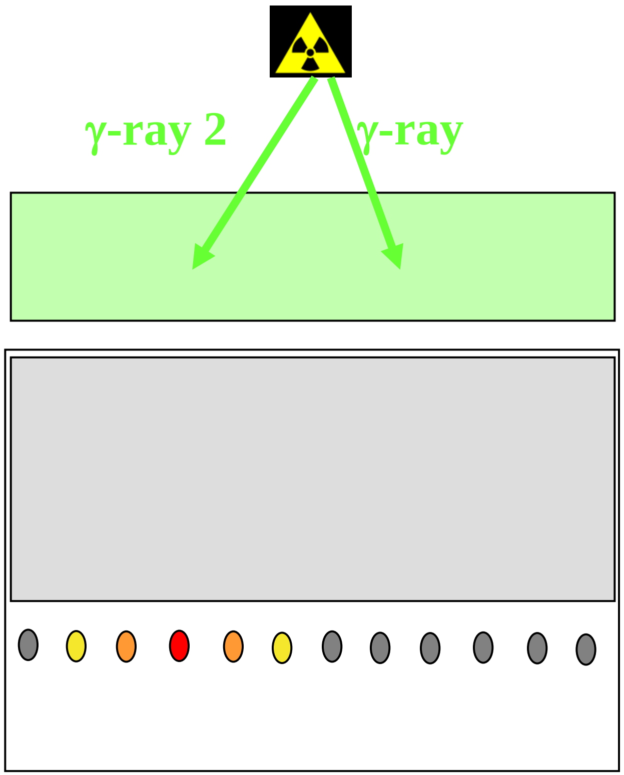

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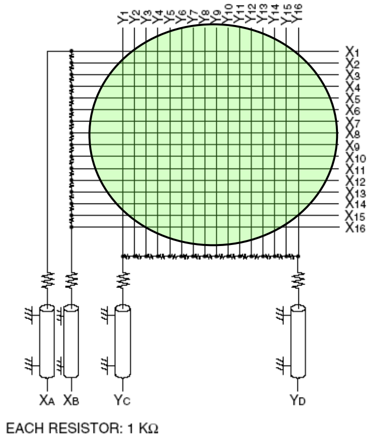
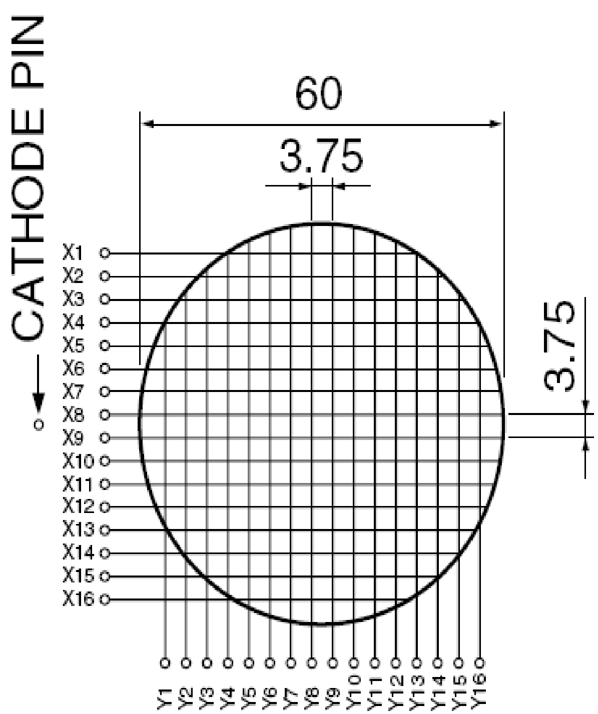


Gamma camera: Individual multi-anode readout

16 wires in X axis and 16 wires in Y axis



ANODE PATTERN
(TOP VIEW)

LYSO scintillator

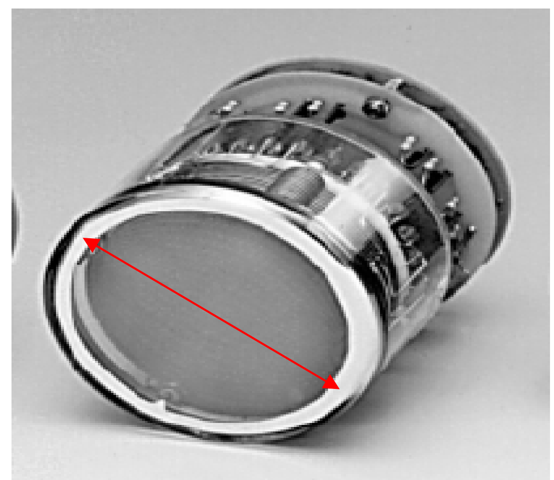
Cerium-doped Lutetium Yttrium Orthosilicate

d = 76 mm

t = 3 mm

$\rho = 7.4$ g/cm^3

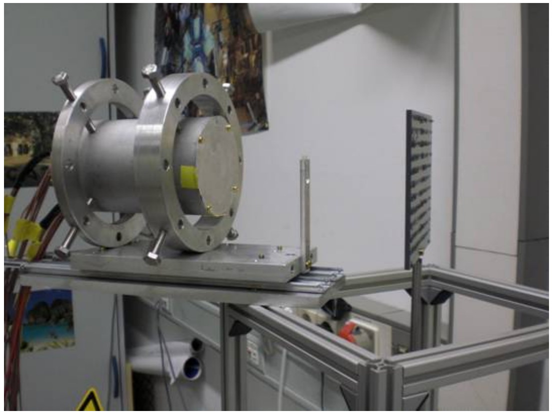
Hamamatsu R2486 PSPMT

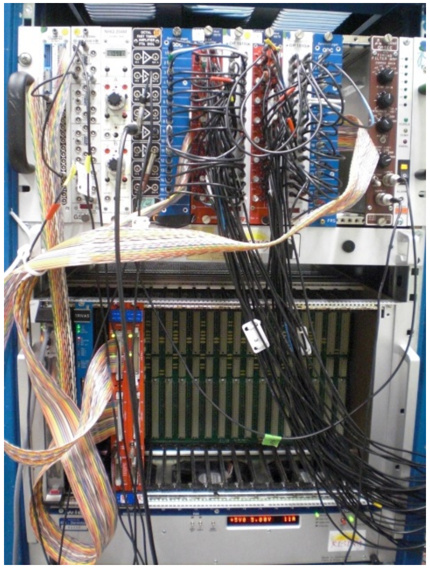


Photocathode = 56.25 mm

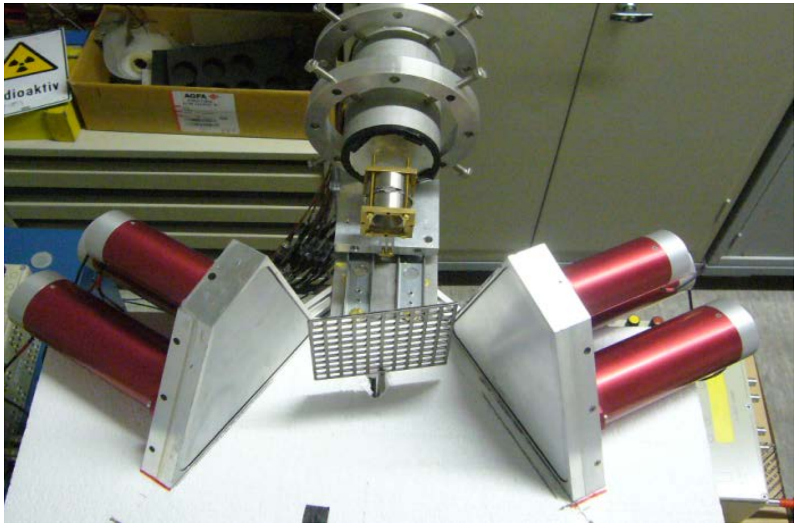
Position calibration

- Determine: $X_r(x_m,y_m)$, $Y_r(x_m,y_m)$



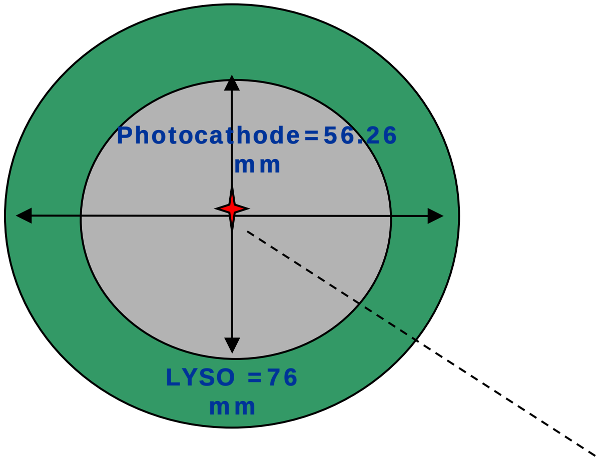


Gamma-ray scattering technique

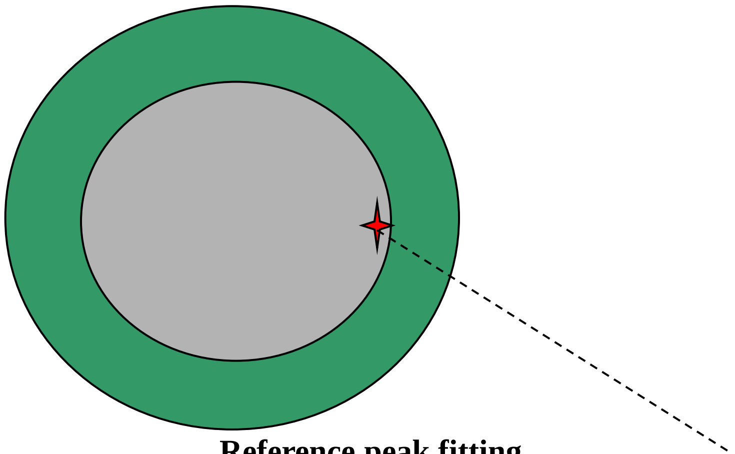


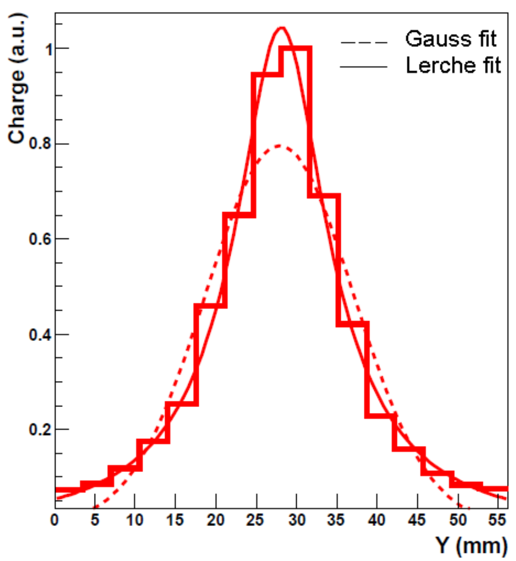
Position reconstruction

Central Interaction

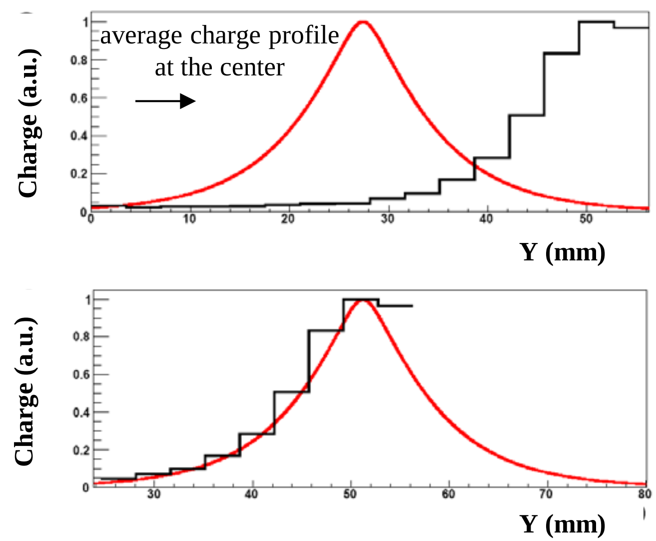


Peripheral Interaction





Reference peak fitting

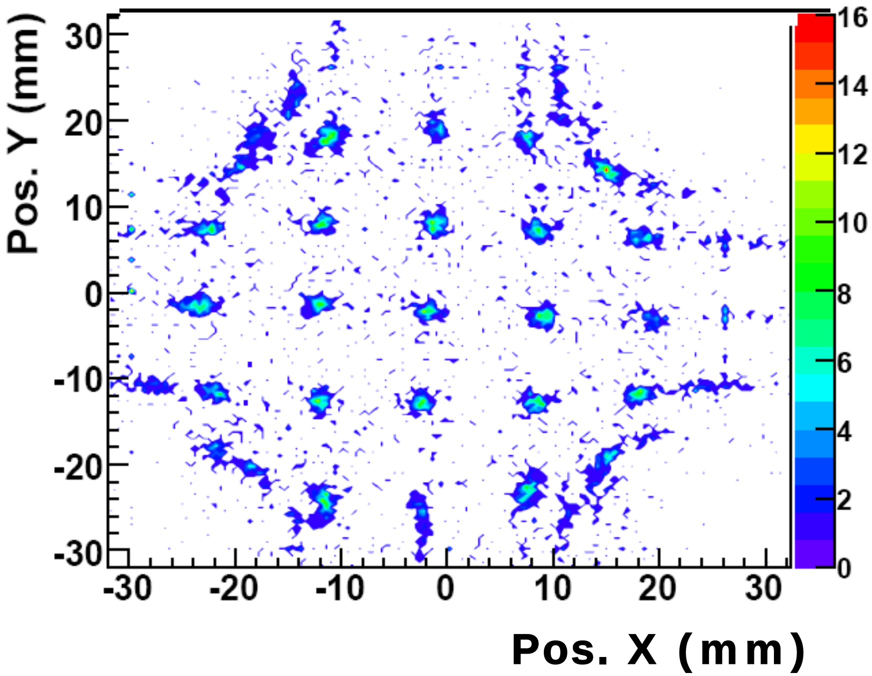


C. Domingo Pardo, N.Goel, et.al., IEEE, Dec. 2009 Volume: 28 Issue 12

C.W.Lerche, et.al., NIM A, Vol 537, pp. 326-330, Jan. 2005

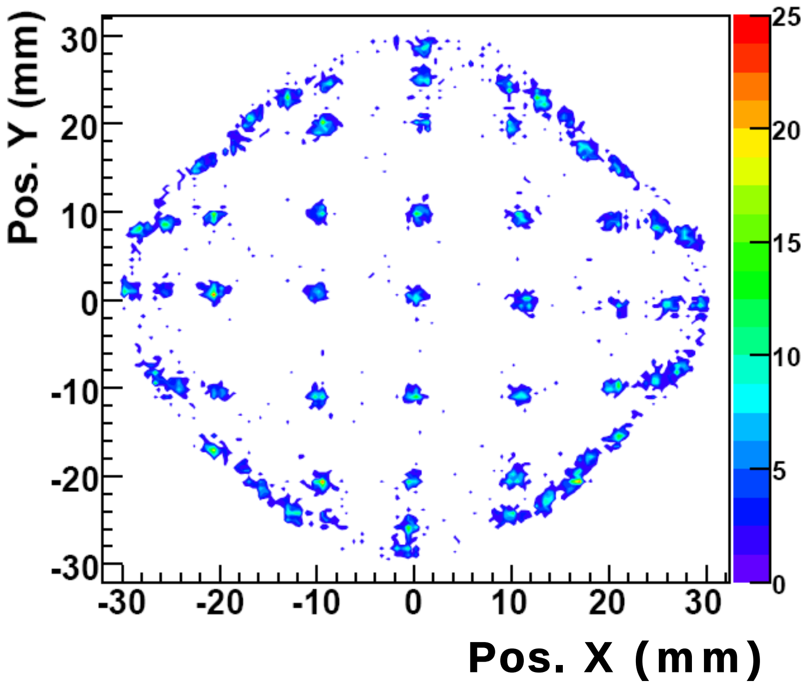
Position reconstruction

Gaussian fitting



Gaussian fitting works relatively well in the central region

Reference peak fitting

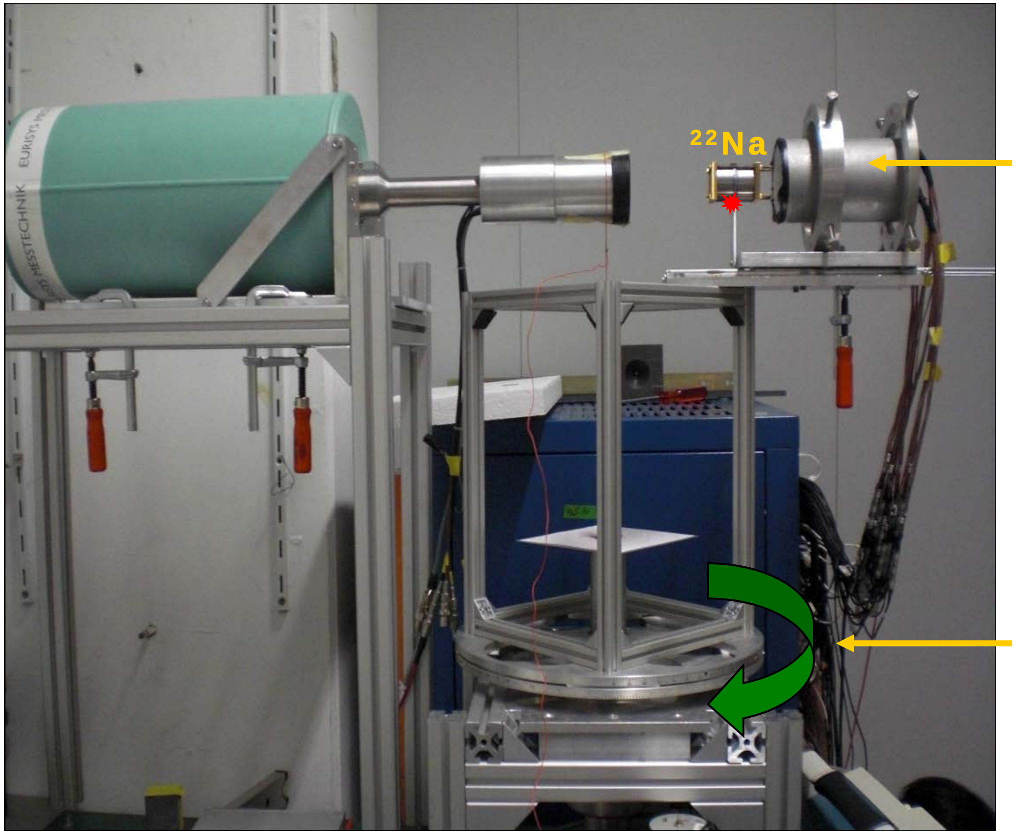


Linear for 50 mm

Field of view = 28 cm^2

Average spatial resolution in X and Y ~ 1mm

Scanner at GSI



Position sensitive detector

Characteristics:

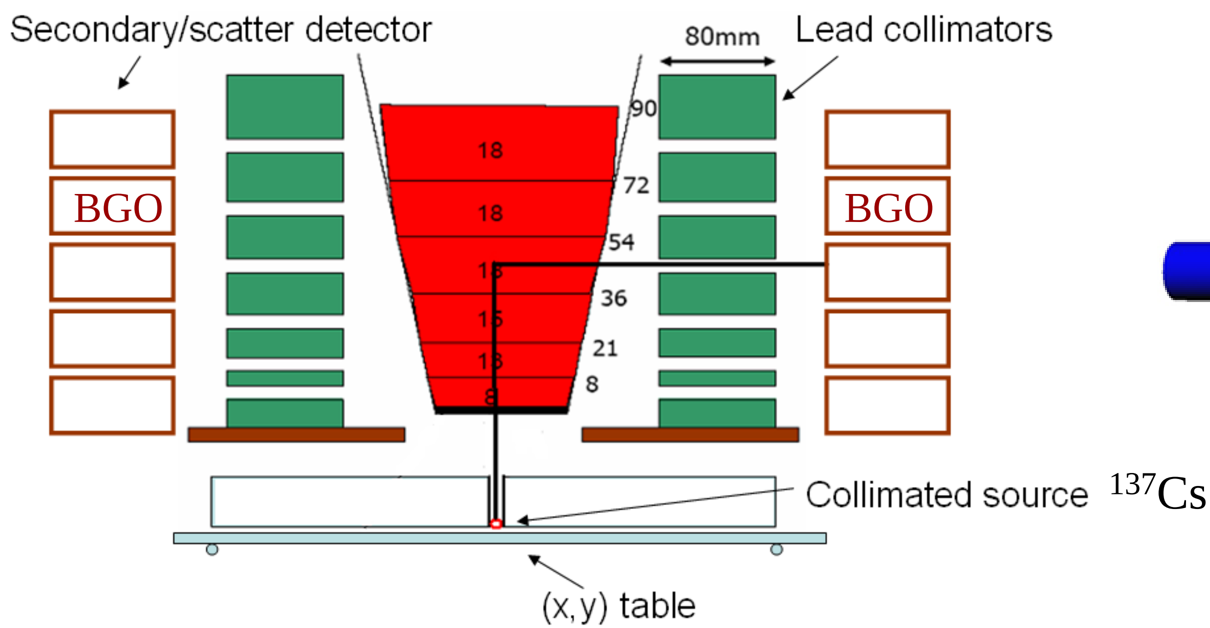
- Faster
- Precision: 1-2 mm
- Imaging capability

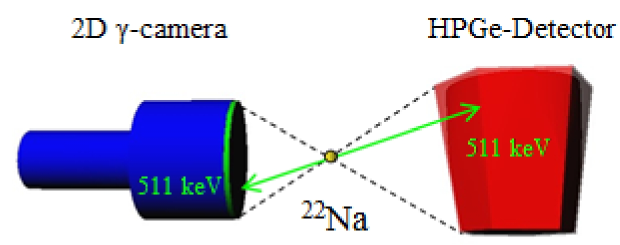
Rotating table

Requirements:
1. Position sensitive detector
   - Excellent Δx/x
   - Large field of view
2. Method to compare the pulses

Superiority over conventional scanner

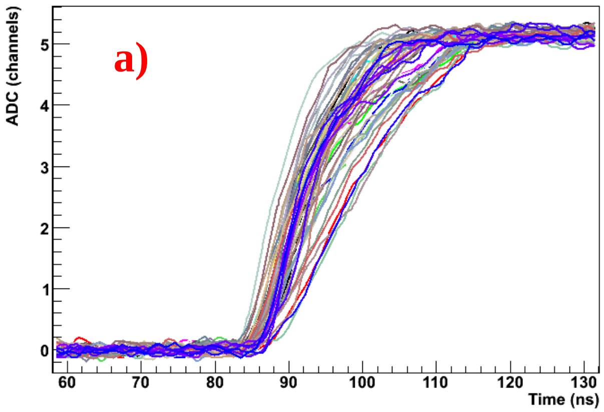
coincidence between the Germanium and BGO detectors for
90 degree Compton scattered events for depth determination

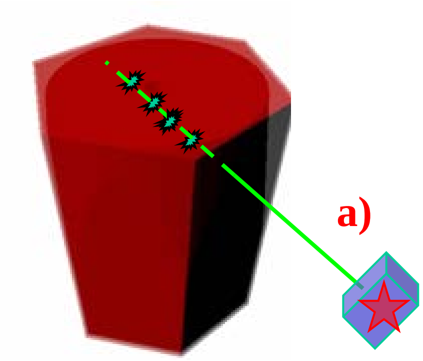




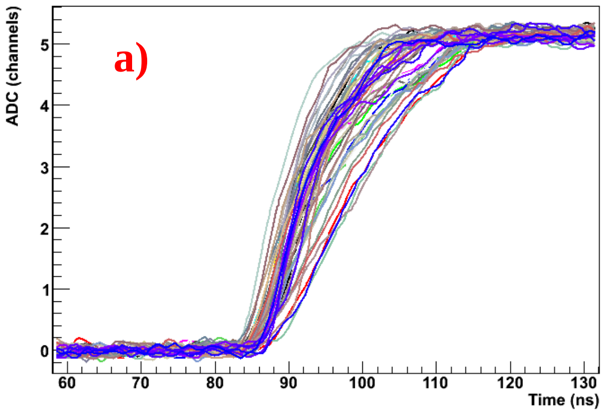
Advantage over conventional scanner: Full detector can be scanned in one measurement
10 times faster than a conventional scanner
Accuracy of simulations can be checked for complex regions of electric field

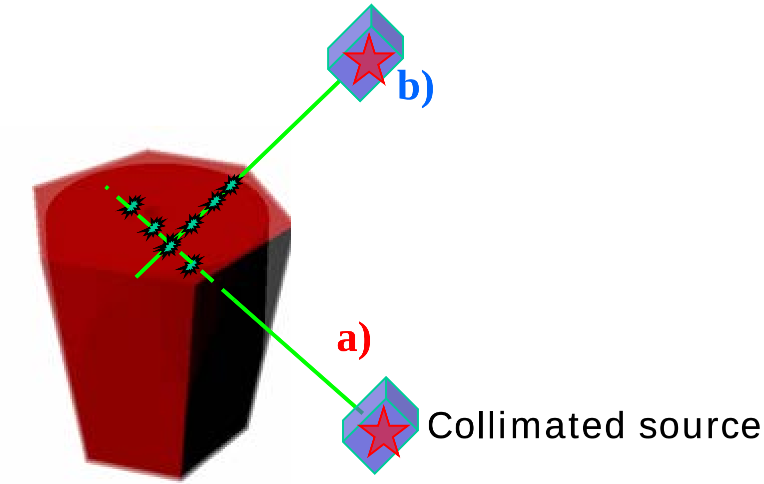
Scanner based on pulse shape comparison scan



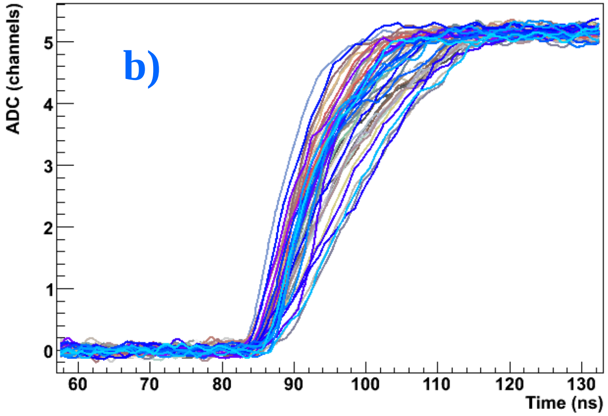


Scanner based on pulse shape comparison scan

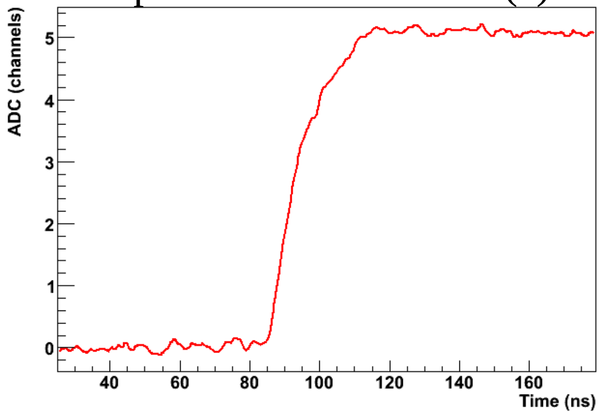




Geometric crossing point: **x,y,z**

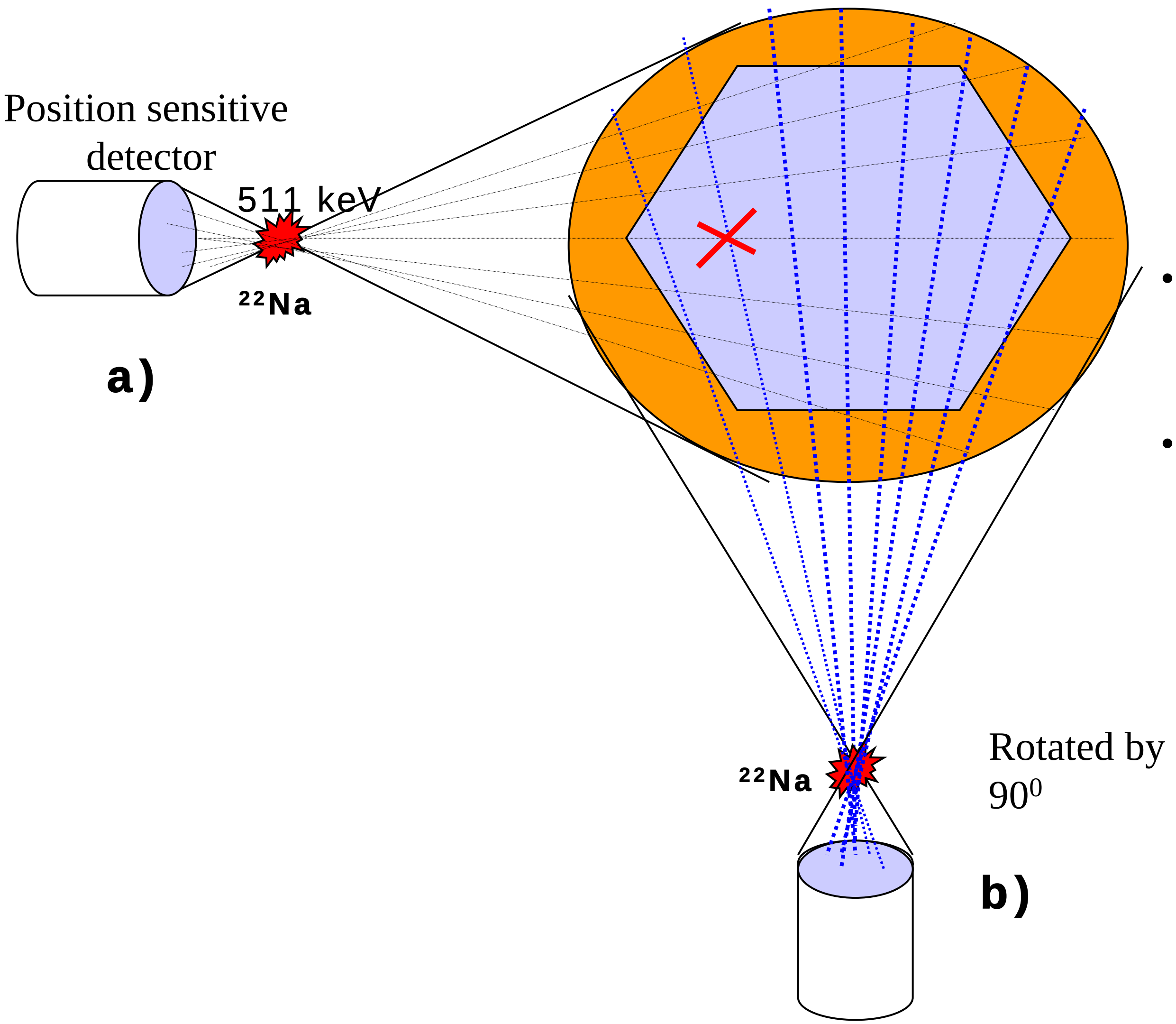


Common pulse out of data sets (a) & (b)



F.C.L. Crespi, et al. NIM A 593 (2008), 440

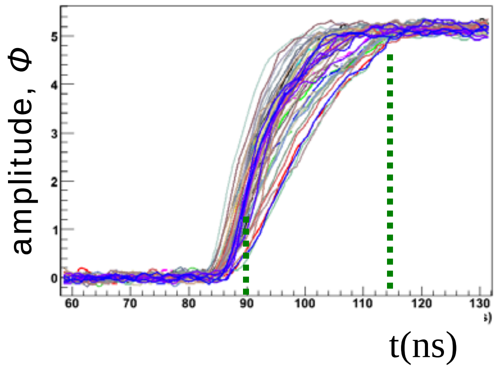
Pulse shape comparison scan method based on a position sensitive detector



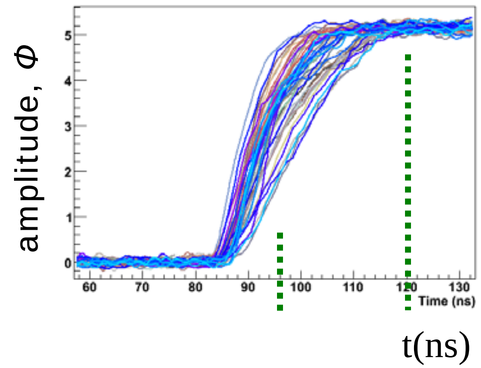
- Recording pulse shapes for positions (a) and (b)
- Identical signals at the crossing point.

χ^2 minimization method

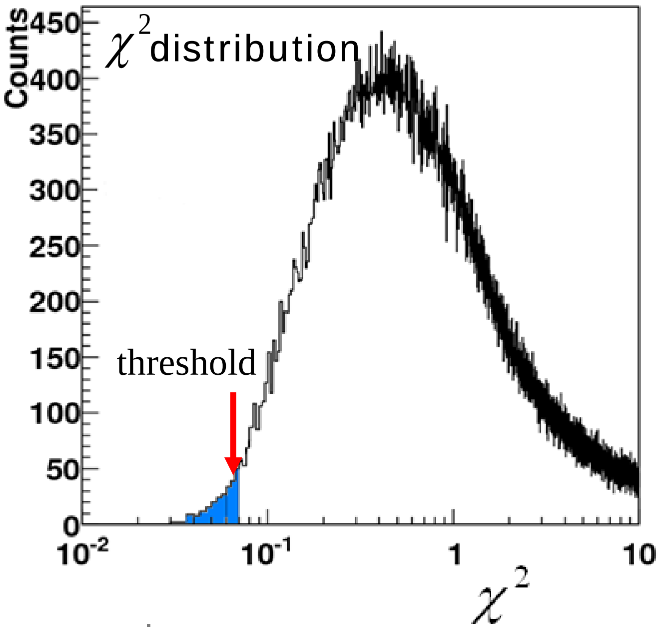
0° measurement



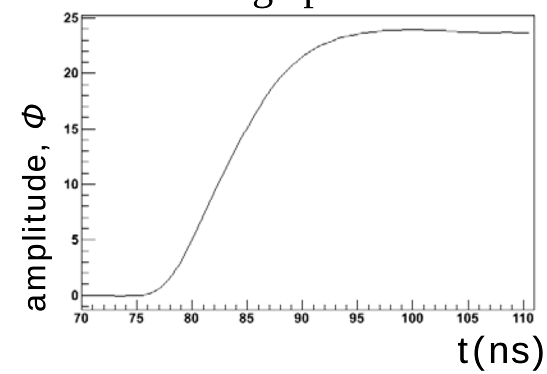
90° measurement



$$\chi^2 = \sum_t (\phi_t^{0°} - \phi_t^{90°})^2$$

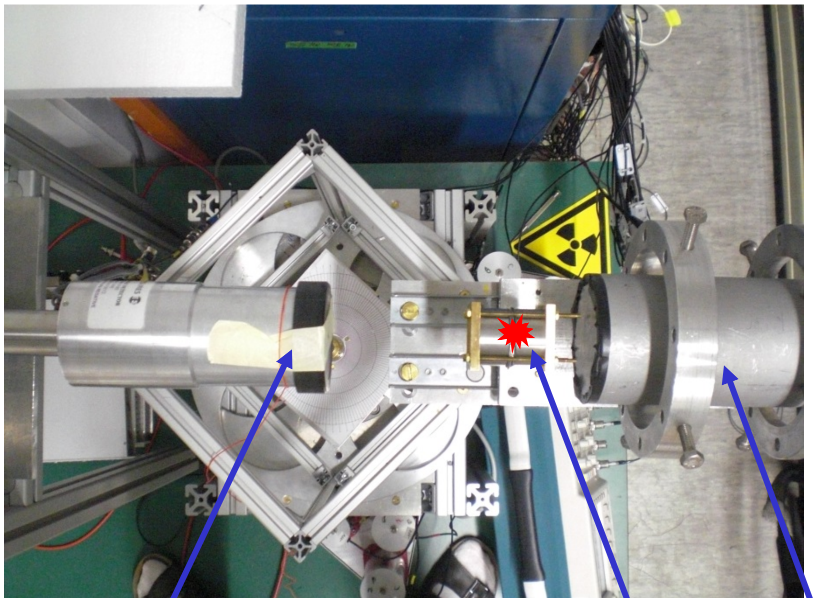


Average pulse

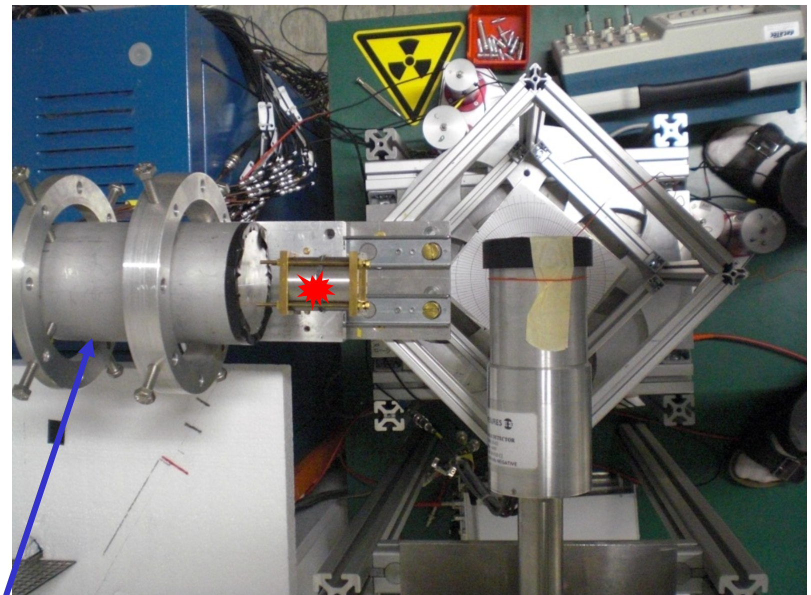


Characterisation of a planar HPGe detector

Front view



Side view



Planar Ge

^{22}Na

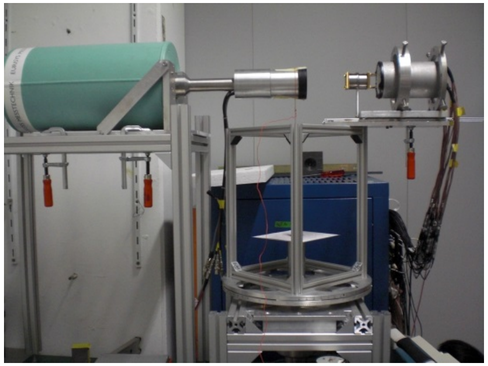
Position sensitive detector

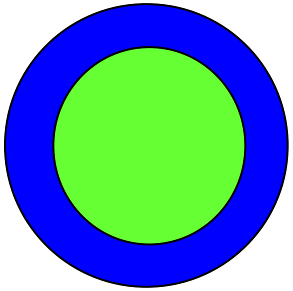
d = 4 cm

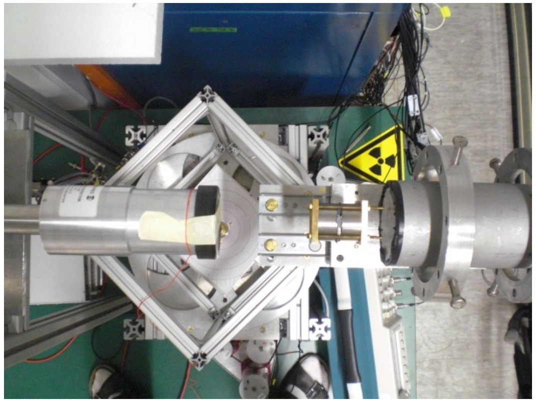
t = 2 cm

Detector scan (test measurements)

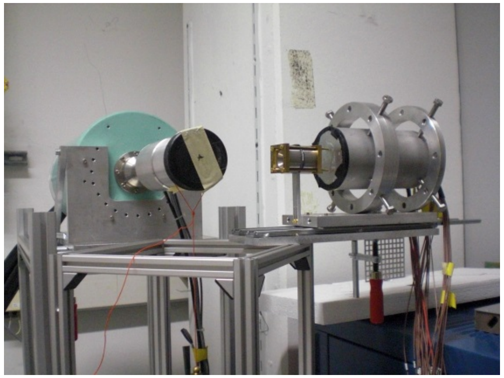
Front view (0 deg):

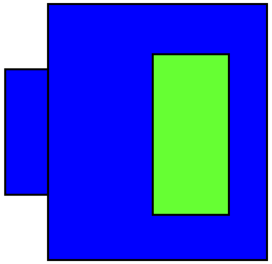


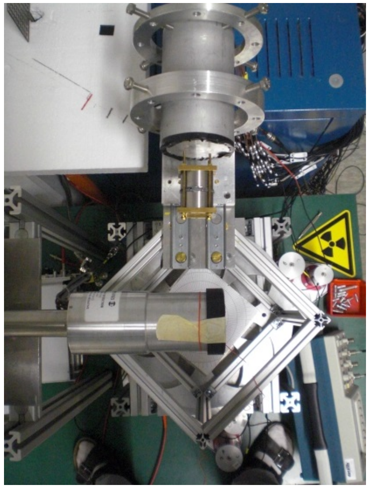




Side view (90 deg):

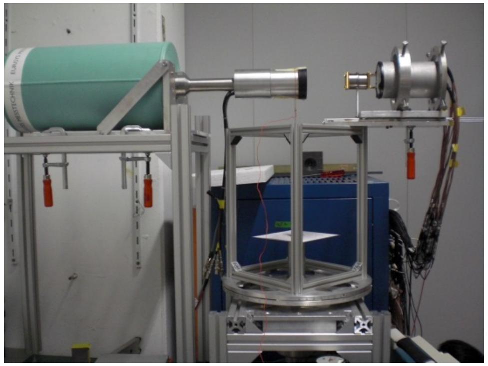


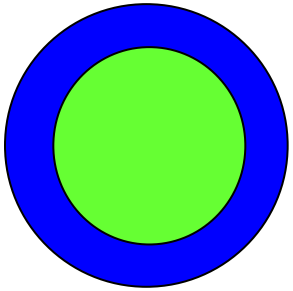


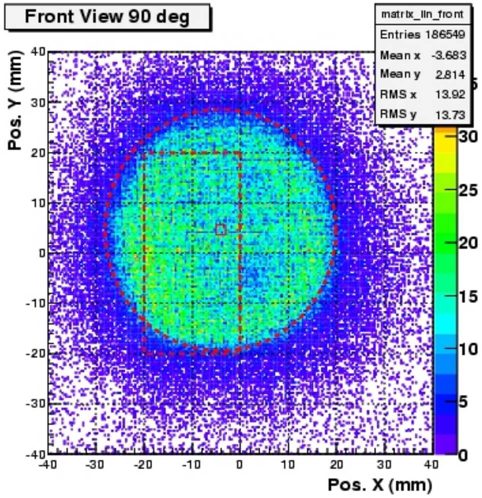


Detector scan (test measurements)

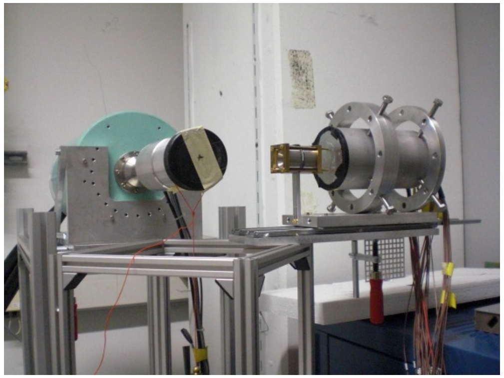
Front view (0 deg):

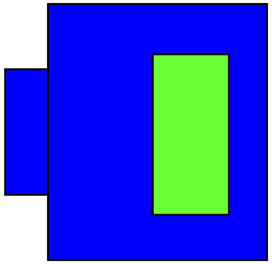


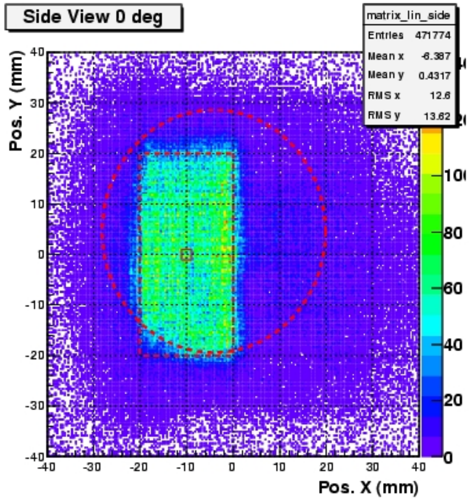




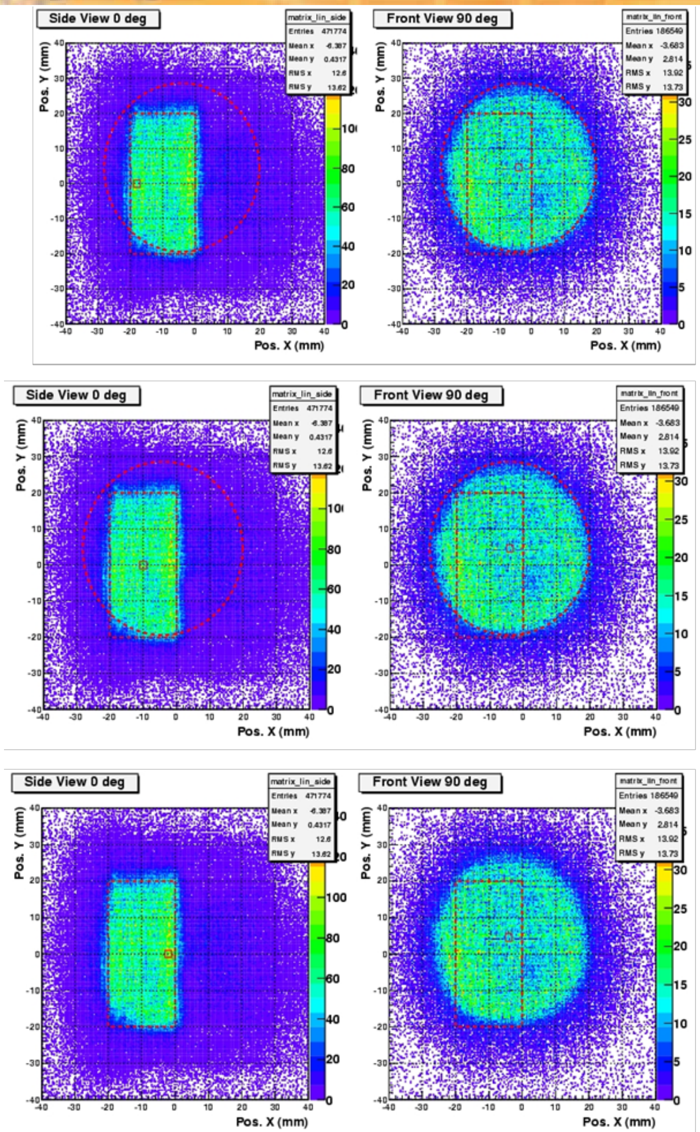
Side view (90 deg):

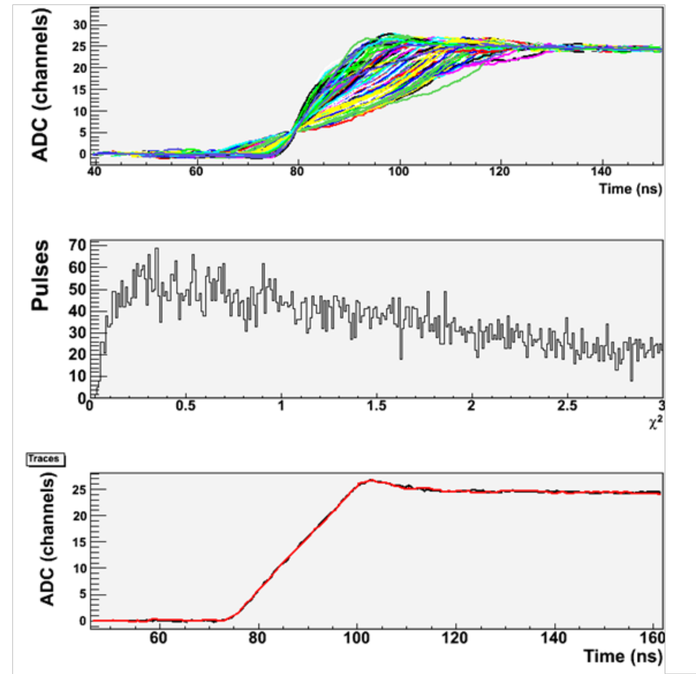


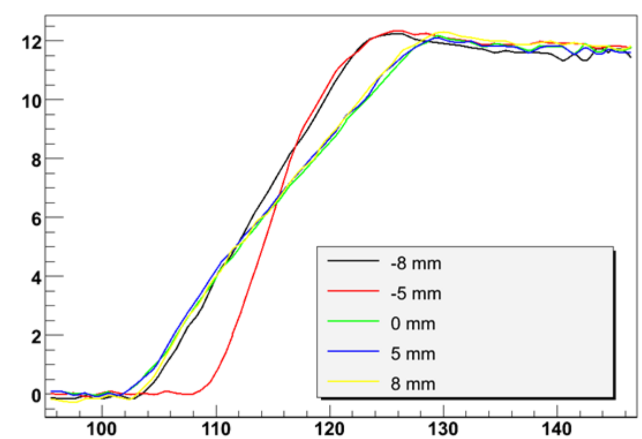




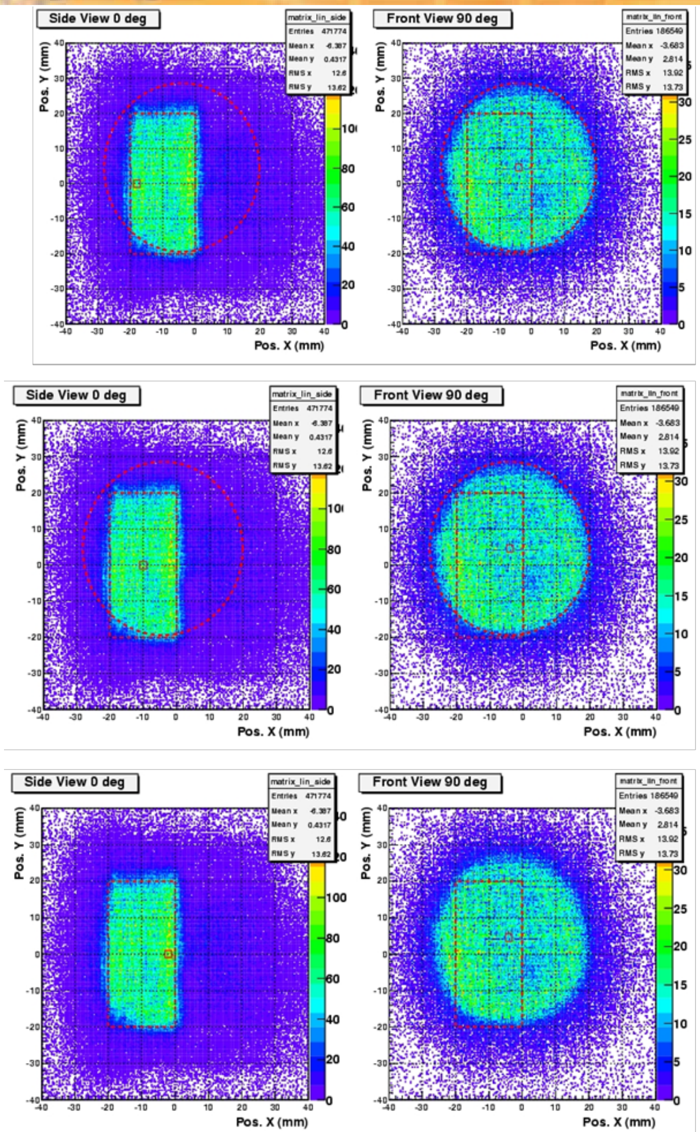
Detector scan (data analysis)

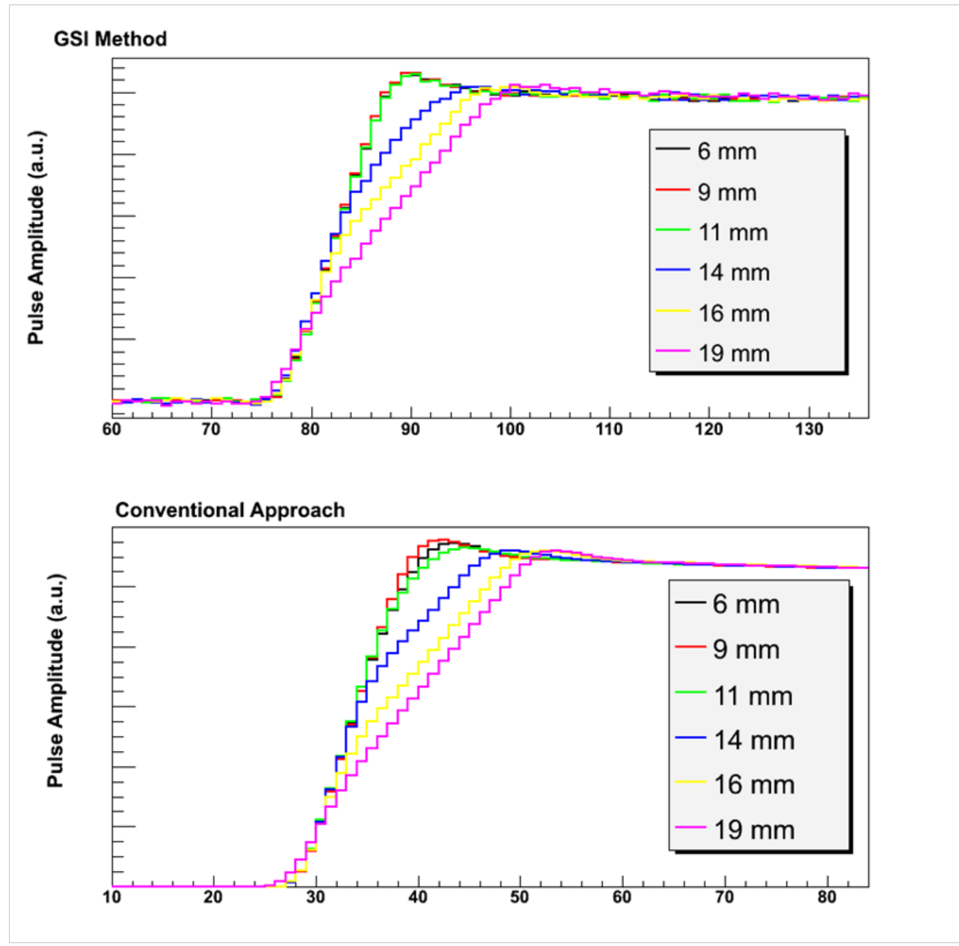






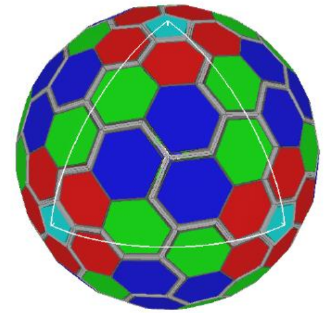
Experimental validation of the method

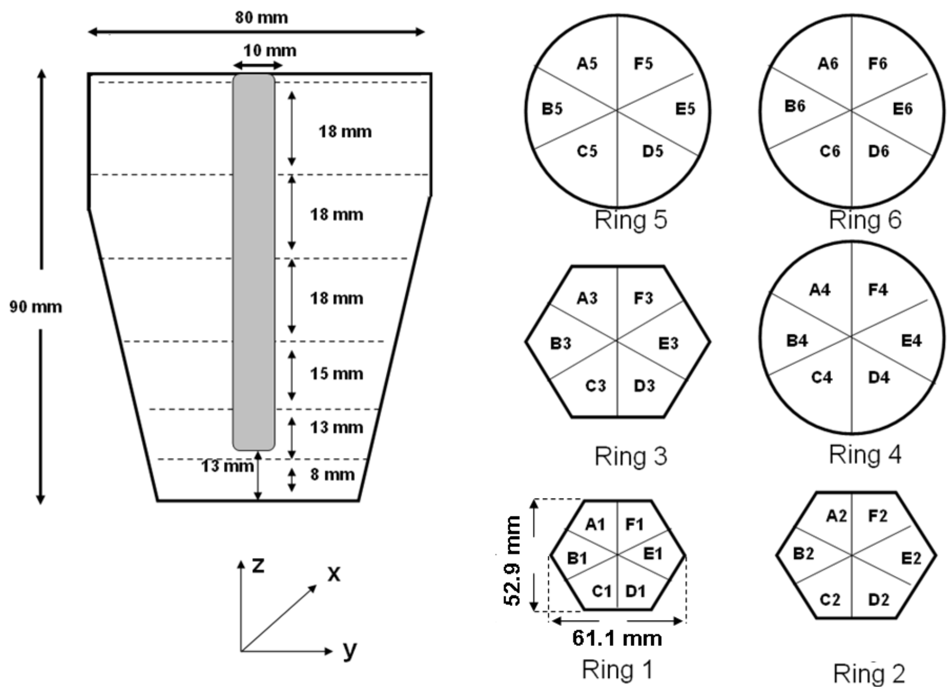




AGATA: Advanced Gamma Tracking Array

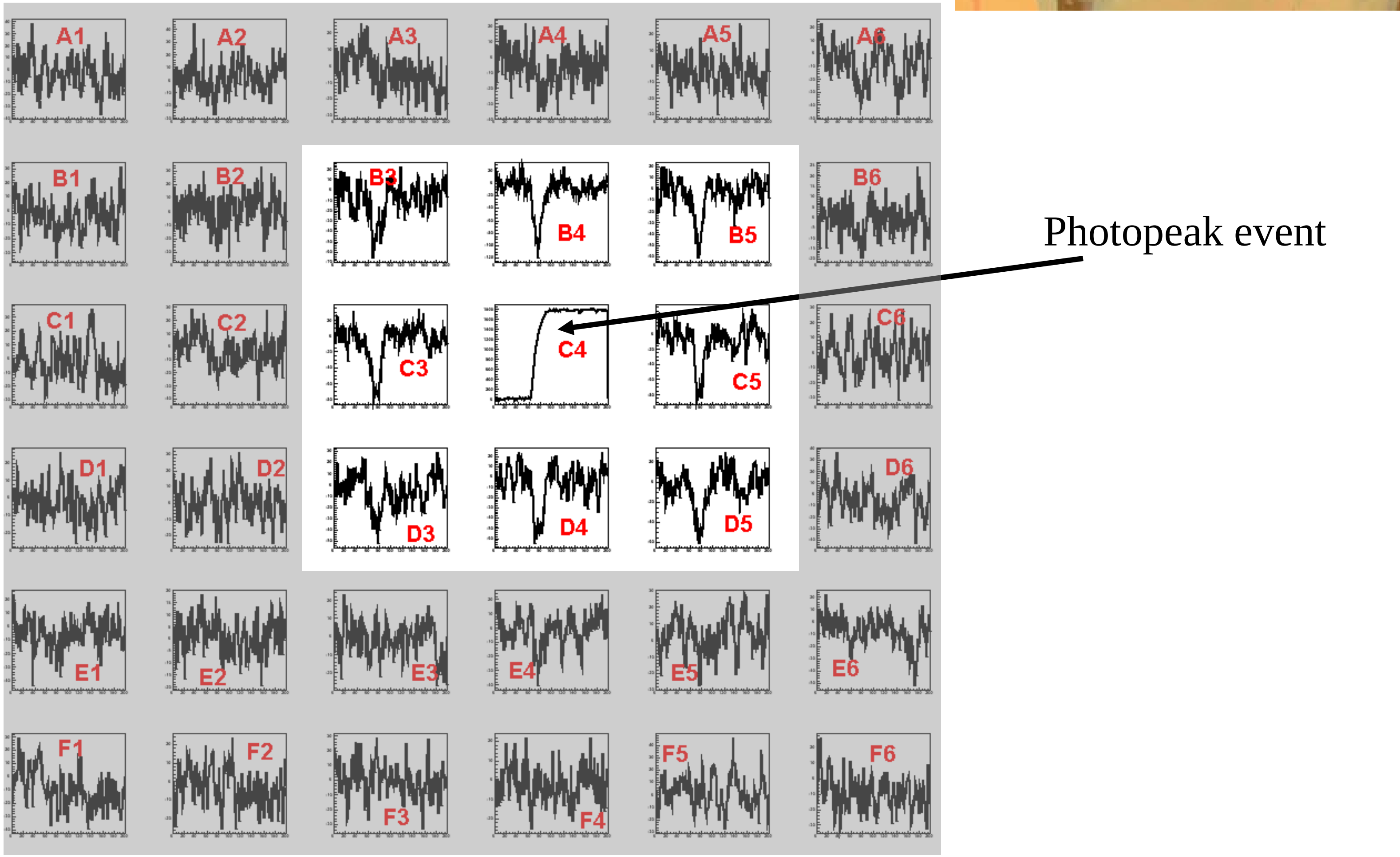
- 4π array of germanium crystals
- 180 segmented crystals arranged around the reaction target
- 3D sensitivity





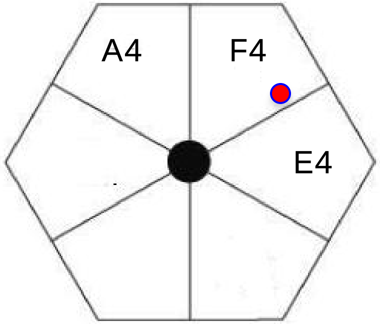
Symmetric AGATA prototype crystal

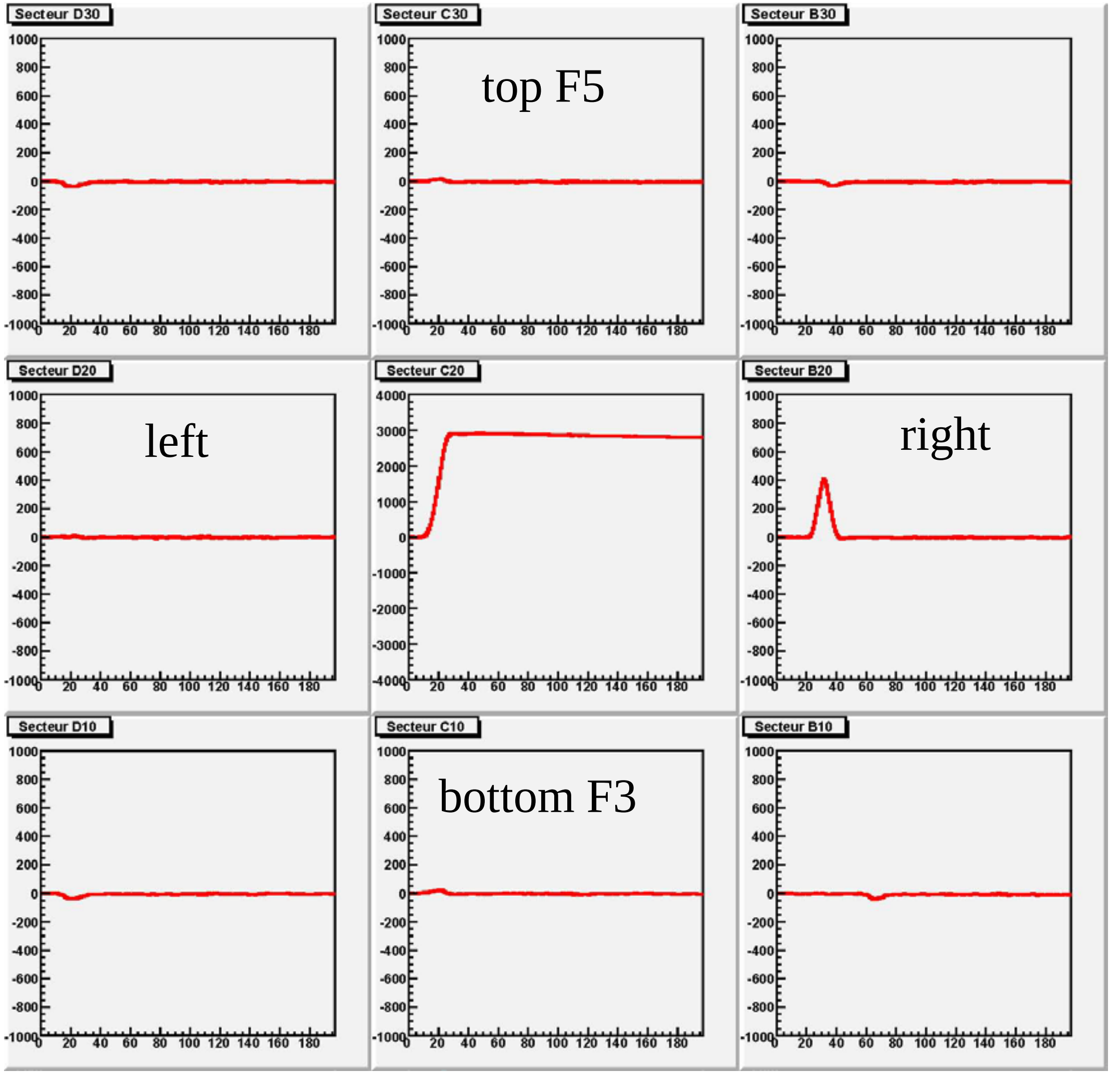
Signal shapes from all 36 segments



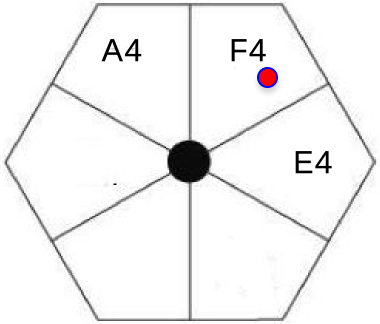
Most significant transient charge signals are from the direct neighbouring segments

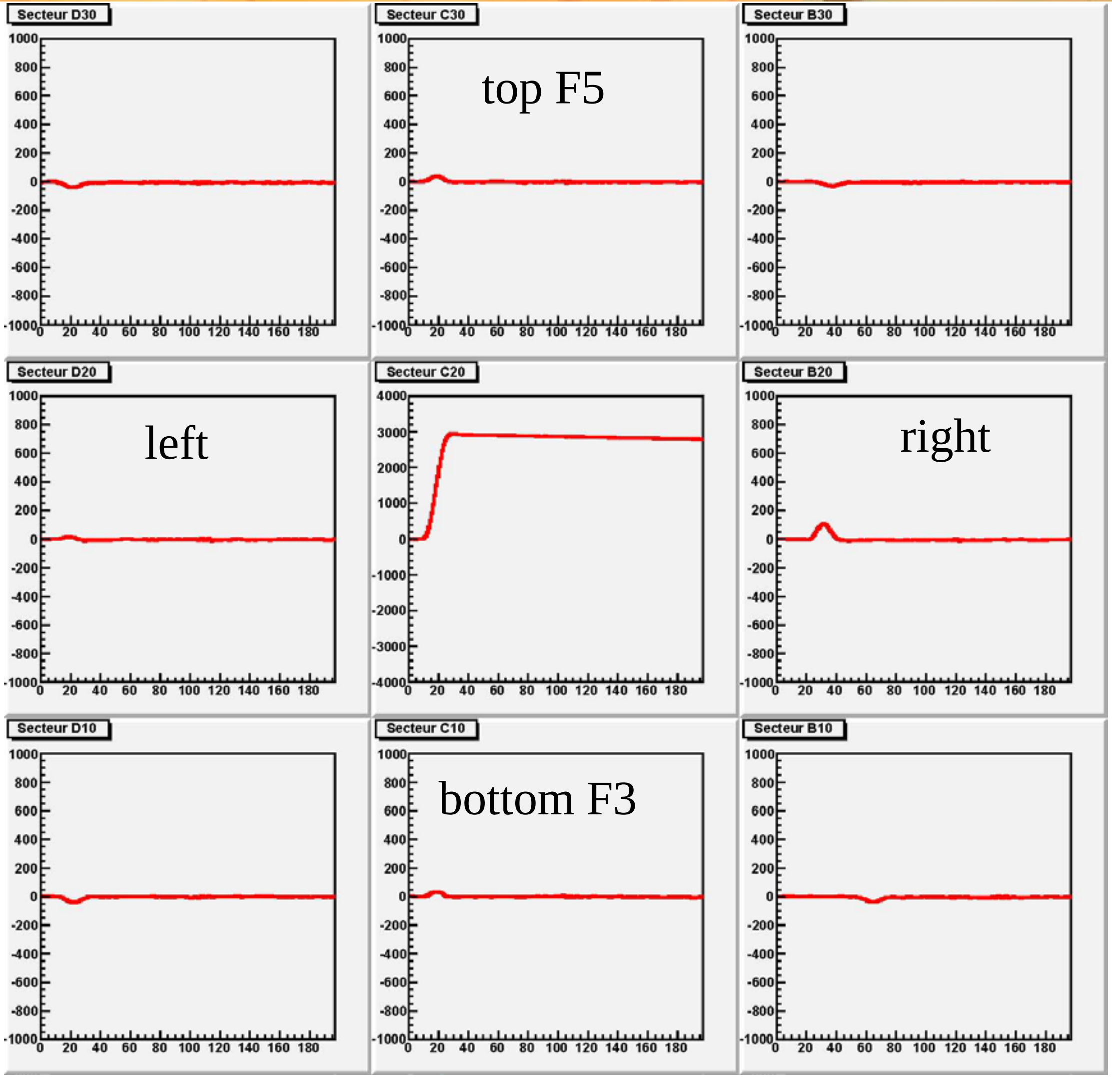
Azimuthal position



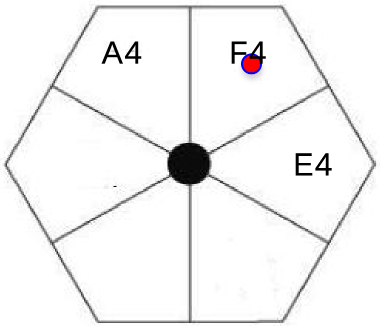


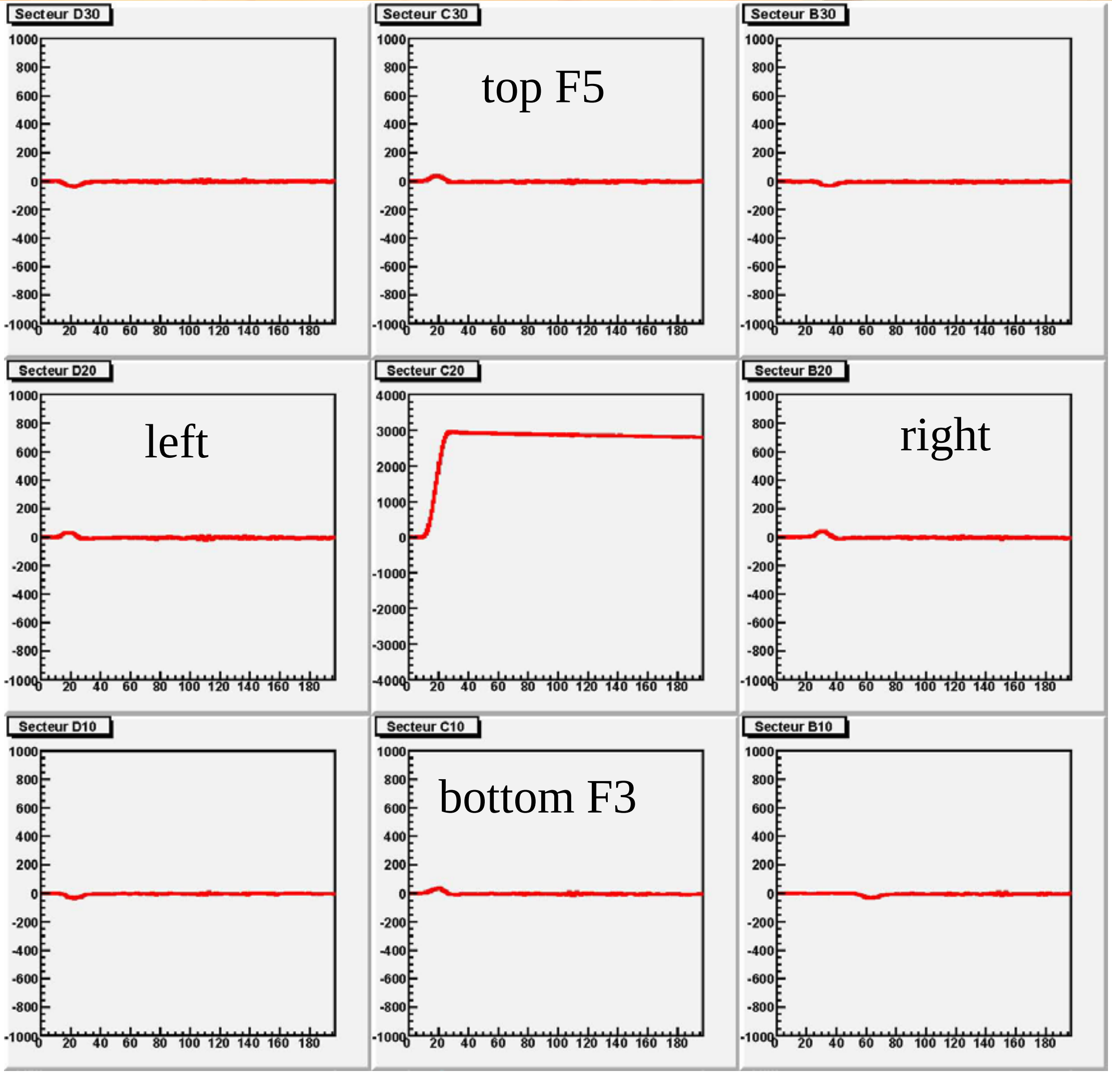
Azimuthal position



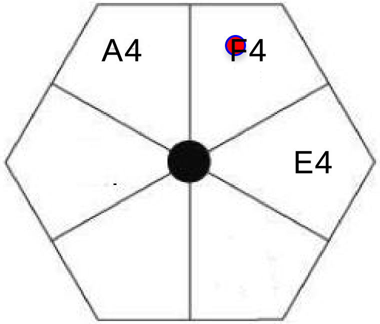


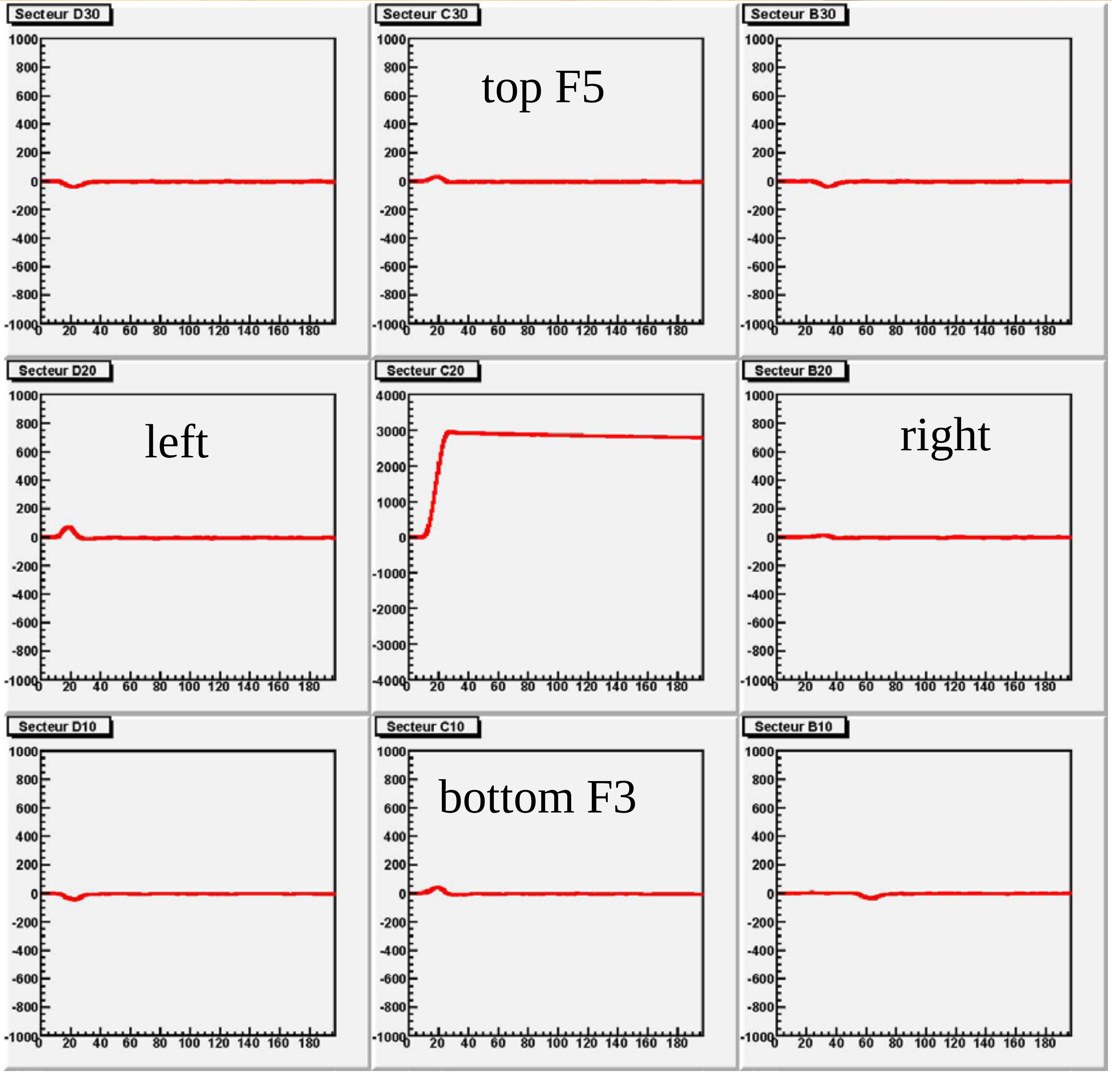
Azimuthal position



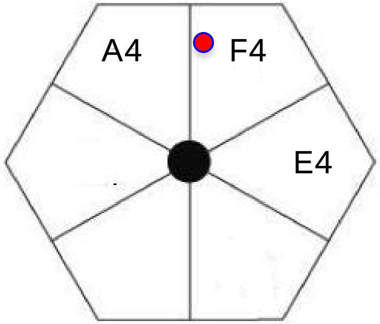


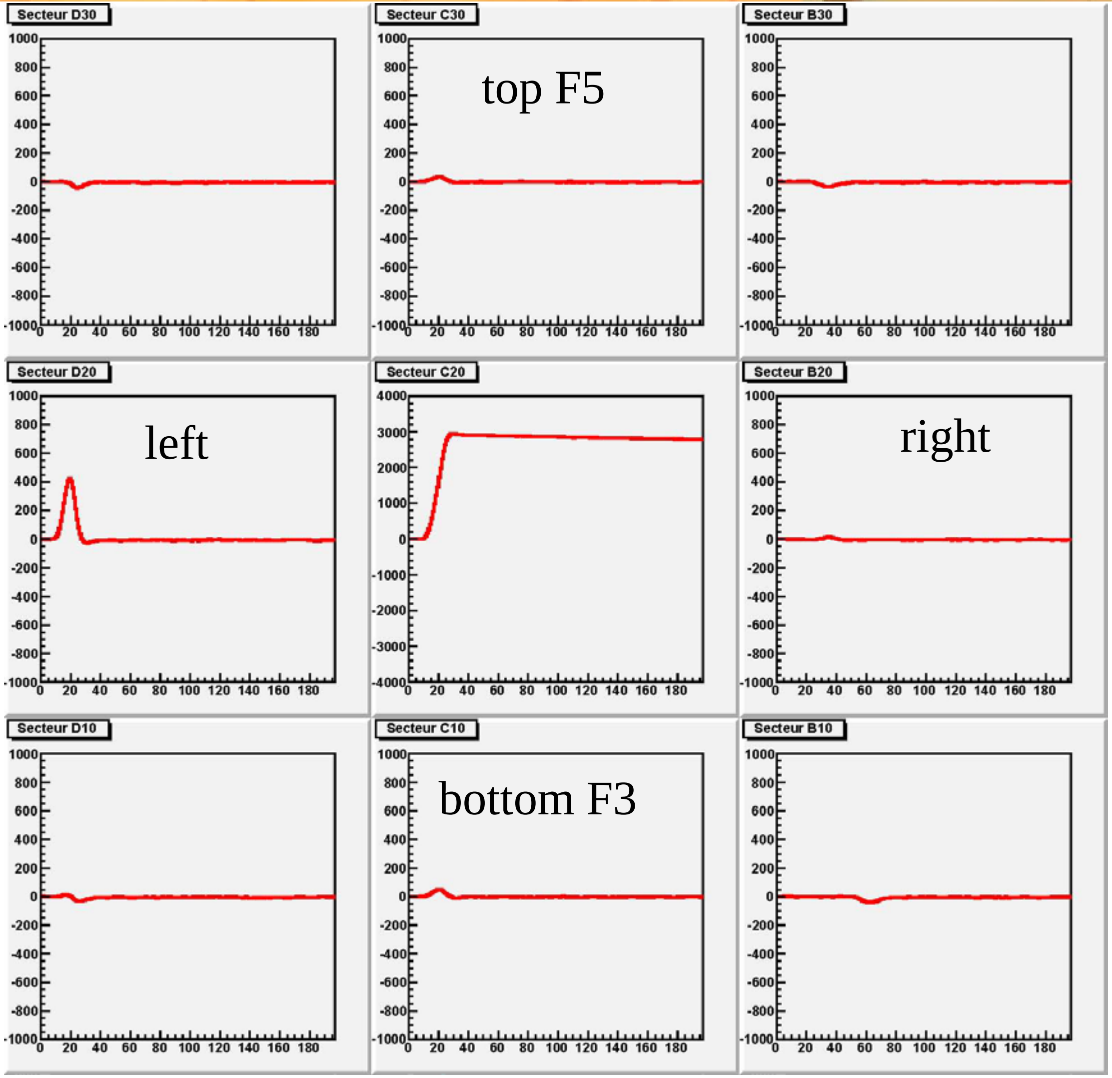
Azimuthal position



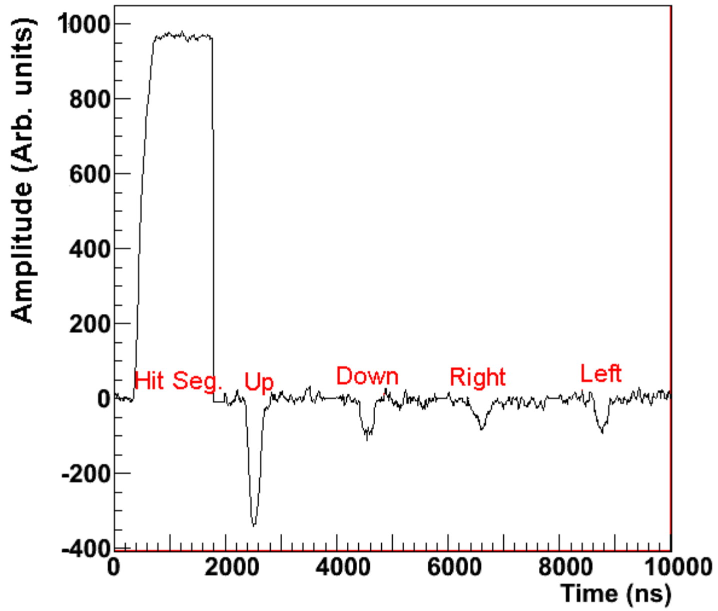


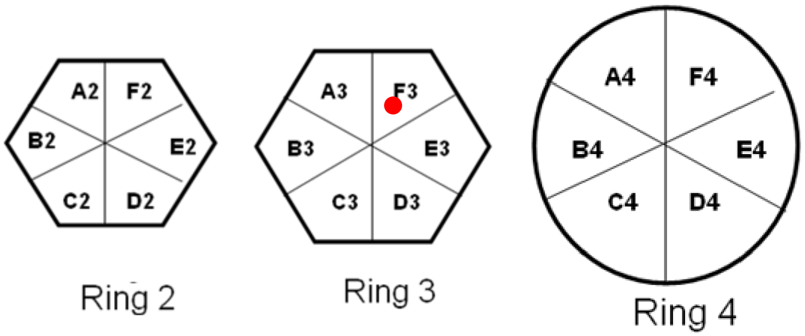
Azimuthal position





Combined trace for pulse shape comparison

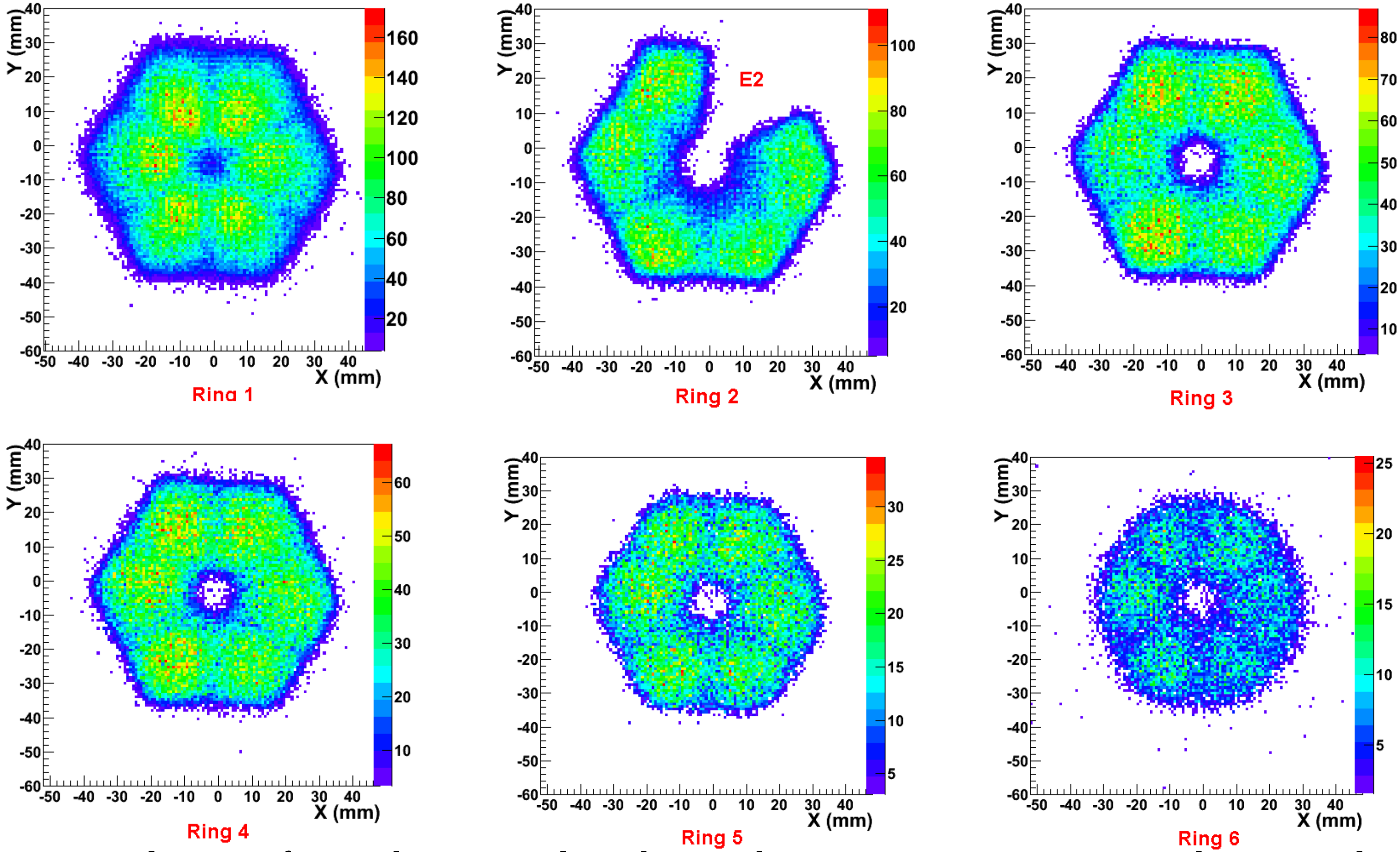




Direct neighbours of segment F3

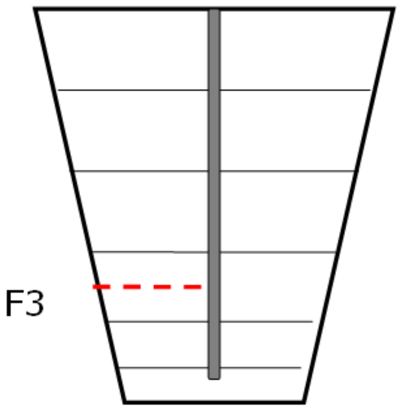
We have the method, the device and the detector ready, lets do the scan of AGATA!

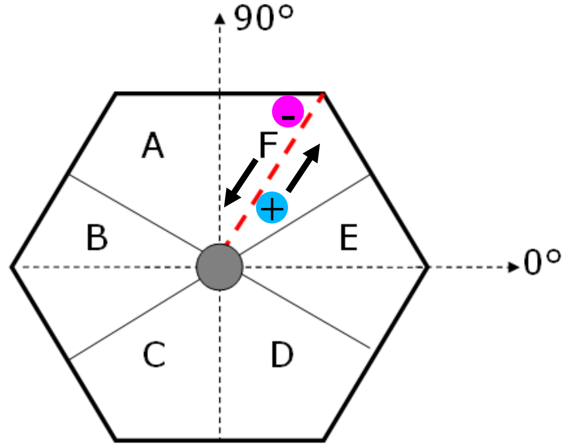
Intensity distribution



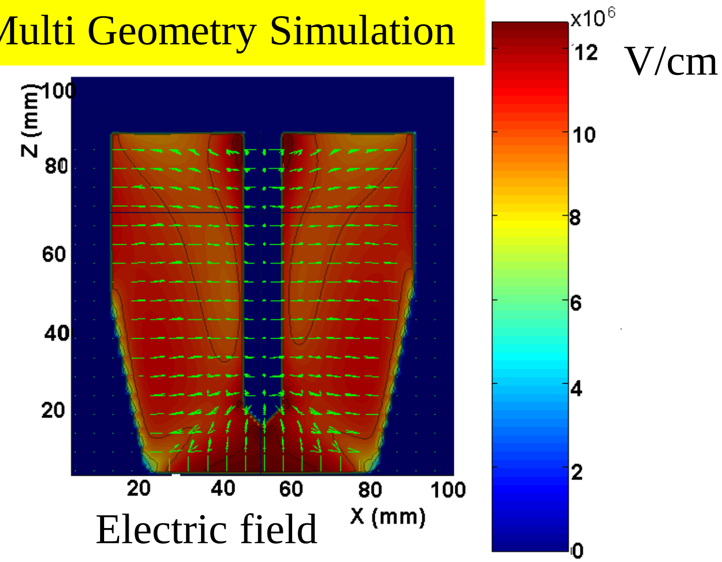
2D projected images for 511 keV coincident photopeak events in position sensitive detector and AGATA

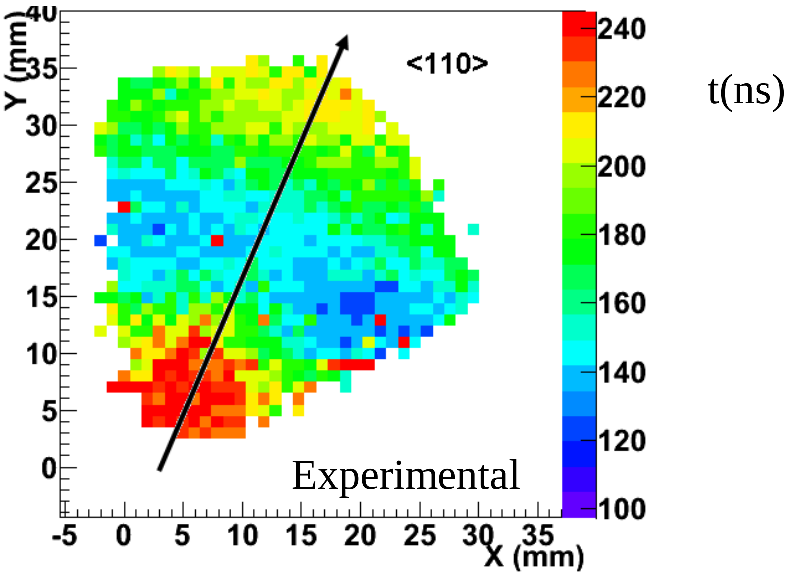
Risetime distribution plots

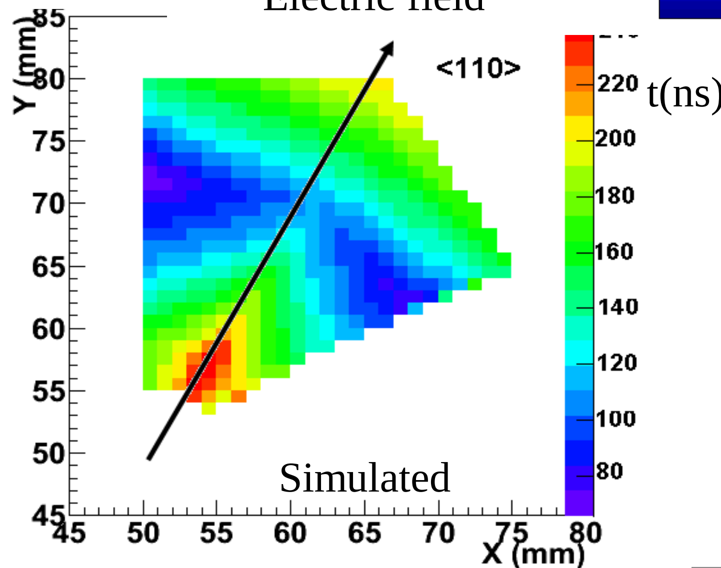




Multi Geometry Simulation

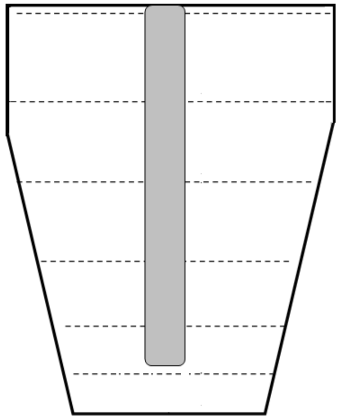


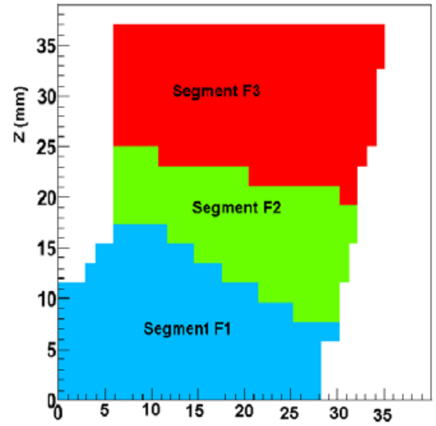




Effective segmentation

Geometric segmentation

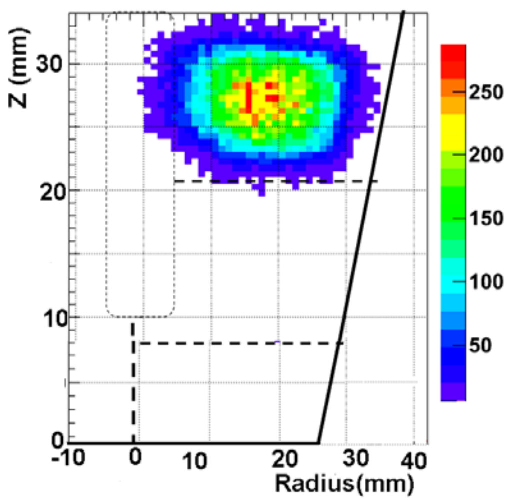




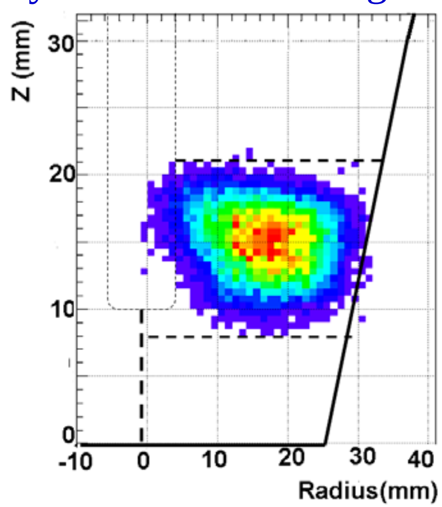
radius (mm)

MGS Segmentation

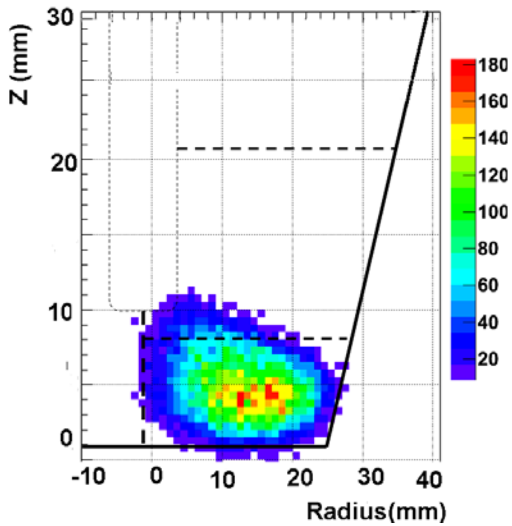
Intensity distribution for segments in row F



Segment F3

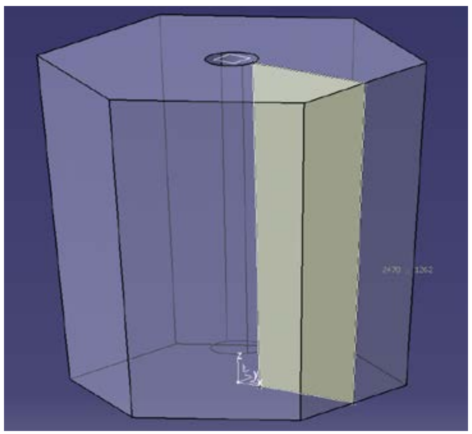


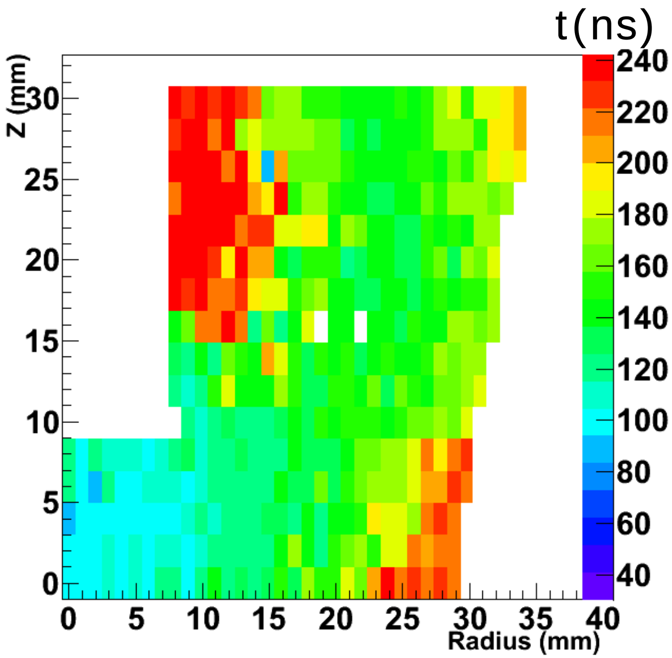
Segment F2



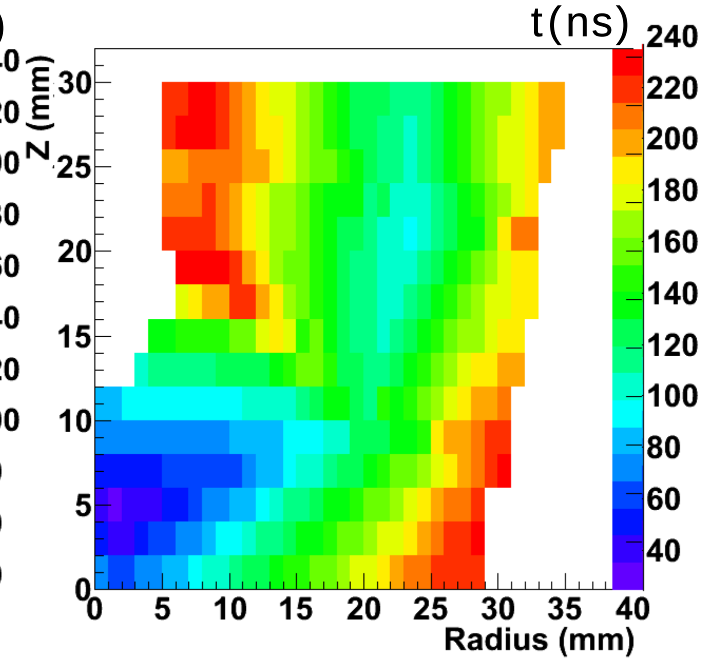
Segment F1

From 2D to 3D: first deep insight into the detector





Experimental



Simulated

Discrepancy in the T90 values near the core in ring 1 ~ 50 ns

Extremely important to have an experimental pulse shape basis for PSA to be applied to the complicated geometries.

Summary & outlook

• We have developed a γ-camera with spatial resolution, linearity and field of view substantially improved with respect to similar existing devices (3 times larger FOV, 2 times better resolution).

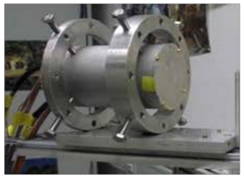
• These improvements in the detection system allow us to characterize the pulse shape of HPGe detectors with an spatial matrix resolution of about 2 mm and in a short period of time (about 2 days per crystal of 9x7 cm^2 size compared to 3 months needed by other approaches).

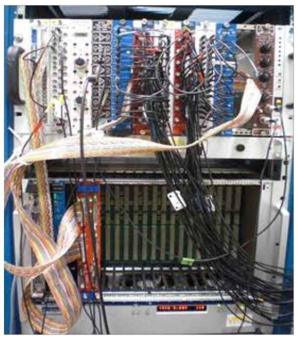
• The good performance of this new detection system makes it very suitable for many γ-ray imaging applications, not only in RIB experiments but also e.g. for medical physics

• Our system uses conventional NIM and VME electronics, which makes it not easily portable, not easily scalable and rather expensive if one wants to build many of these devices. However, this drawback could be overcome thanks to the increasing technology of electronics, e.g. a new acquisition system based on ASIC, FPGA, etc technologies. This would also make the system more suitable for medical applications.

• Applications with thicker scintillation crystals (1 cm) may become possible, without compromising its good performance, thanks to the more accurate measurement of the DOI. (Tests are in progress).

Summary & outlook





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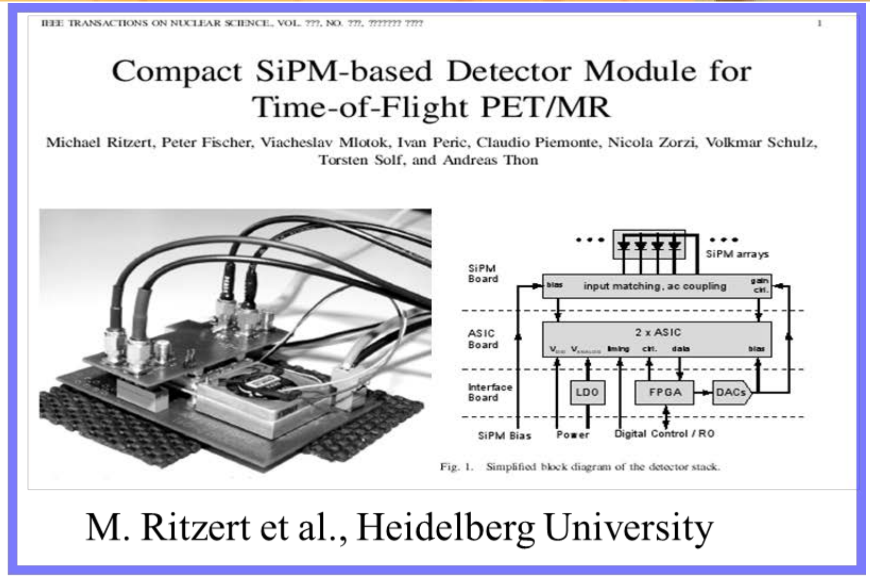

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Compact SiPM-based Detector Module for Time-of-Flight PET/MR

Michael Ritzert, Peter Fischer, Viacheslav Mlotok, Ivan Peric, Claudio Piemonte, Nicola Zorzi, Volkmar Schulz, Torsten Solf, and Andreas Thon

Fig. 1. Simplified block diagram of the detector stack.

M. Ritzert et al., Heidelberg University

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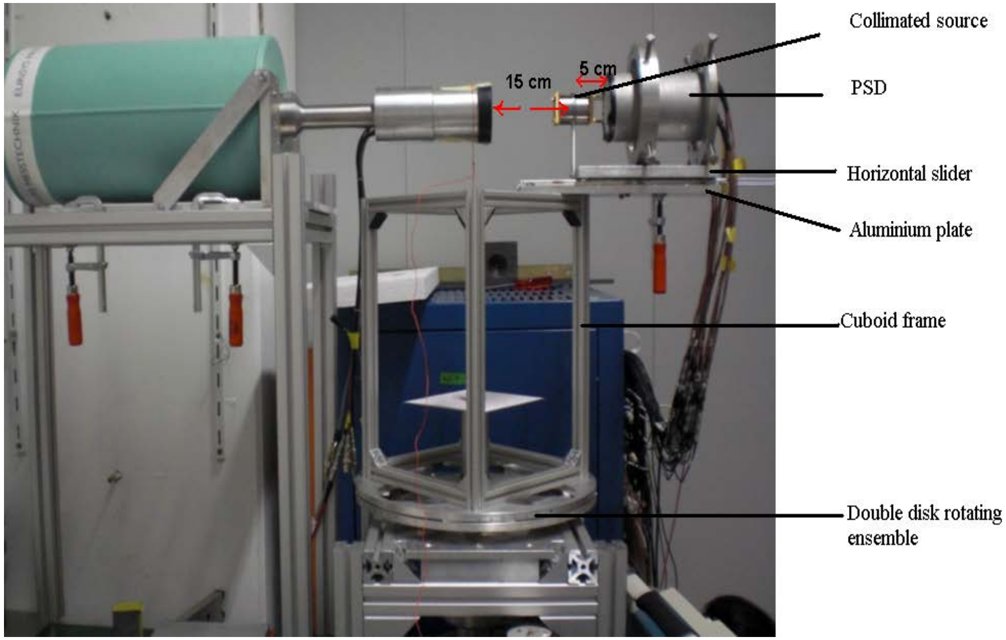
Conclusion and summary

- 1.Next generation of segmented HPGe based gamma arrays
- for inflight spectroscopy
- 2.Pulse shape analysis and gamma ray tracking
- 3.A novel scanner based on pulse shape comparison scan



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- 1.Next generation of segmented HPGe based gamma arrays
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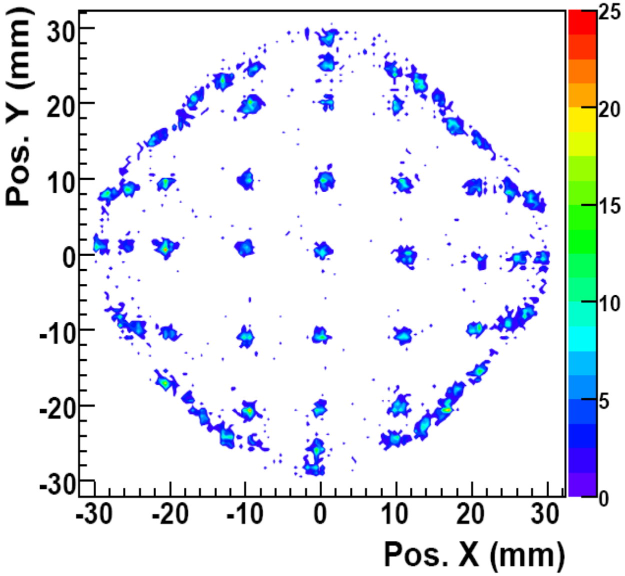
- 4.Development of a gamma camera to achieve superior
- position resolution of 1 mm



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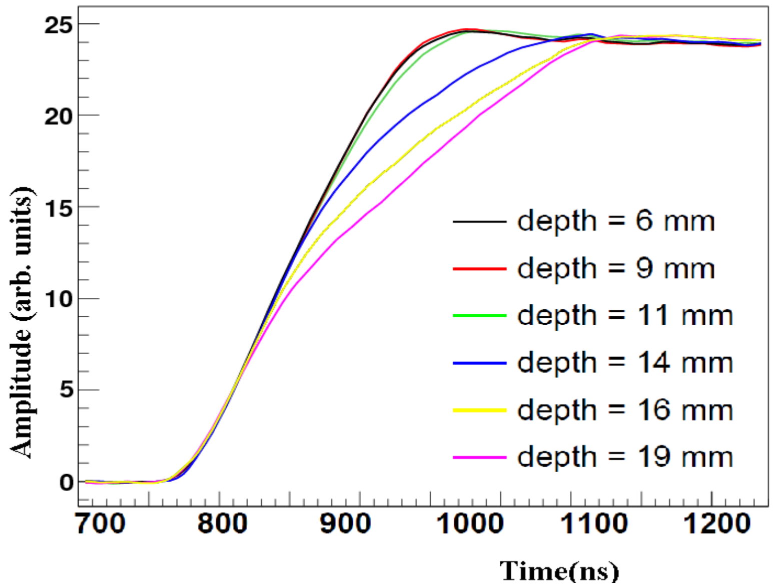
- 5.Succesful test with a planar HPGe crystal



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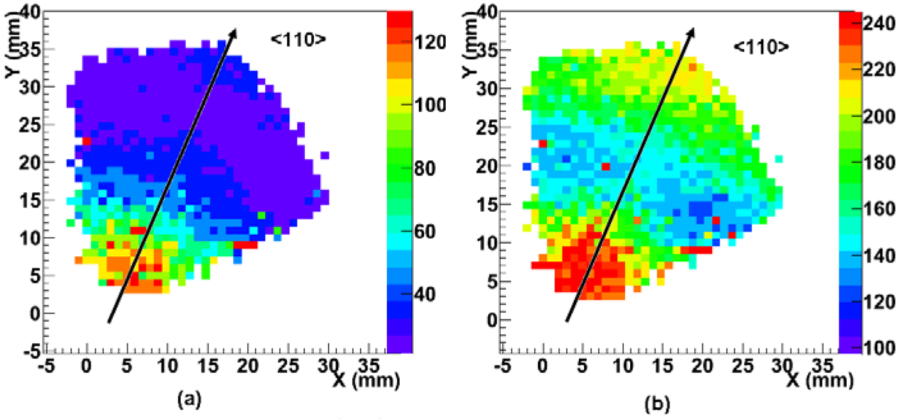

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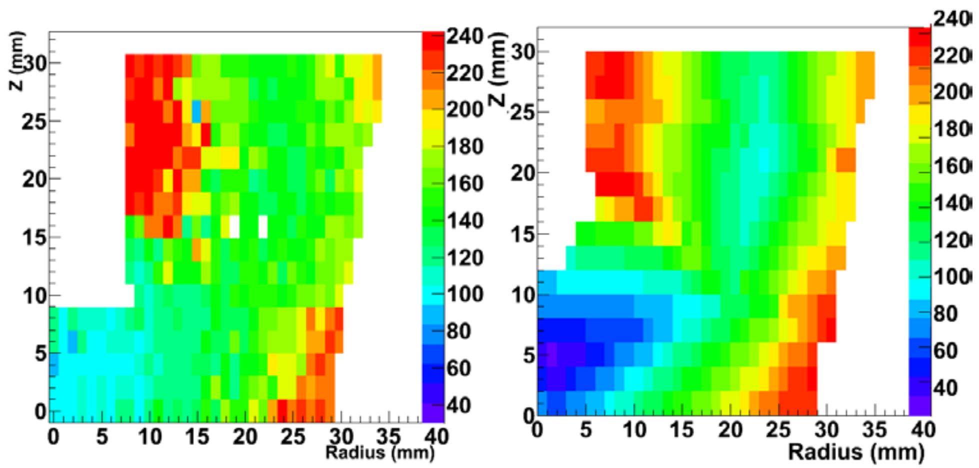

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- 8.Implement signal basis for PSA