# The Use of Neutron Generators for the Detection of Illicit Materials in the Sea Transportation System

G. Nebbia [1) ] , M. Lunardon [1) ] , S. Moretto [1) ] , S. Pesente [1) ] , G. Viesti [1) ] , A. Fontana [2) ] , A. Zenoni [2) ] , M. Cinausero [3) ] , S. Blagus [4) ] , K. Nad [4) ] , J. Obodhas [4) ] , D. Sudac [4) ] , V. Valkovic [4) ] , D. Matika [5) ]

1) I.N.F.N. and Dip. di Fisica, Universita' di Padova, Italy
2) I.N.F.N. Pavia and Dip. di Ingegneria, Universita' di Brescia, Italy
3) I.N.F.N. Laboratori Nazionali di Legnaro, Italy
4) Institute Ruder Boskovic, Zagreb, Croatia
5) Department of Defence, Croatia

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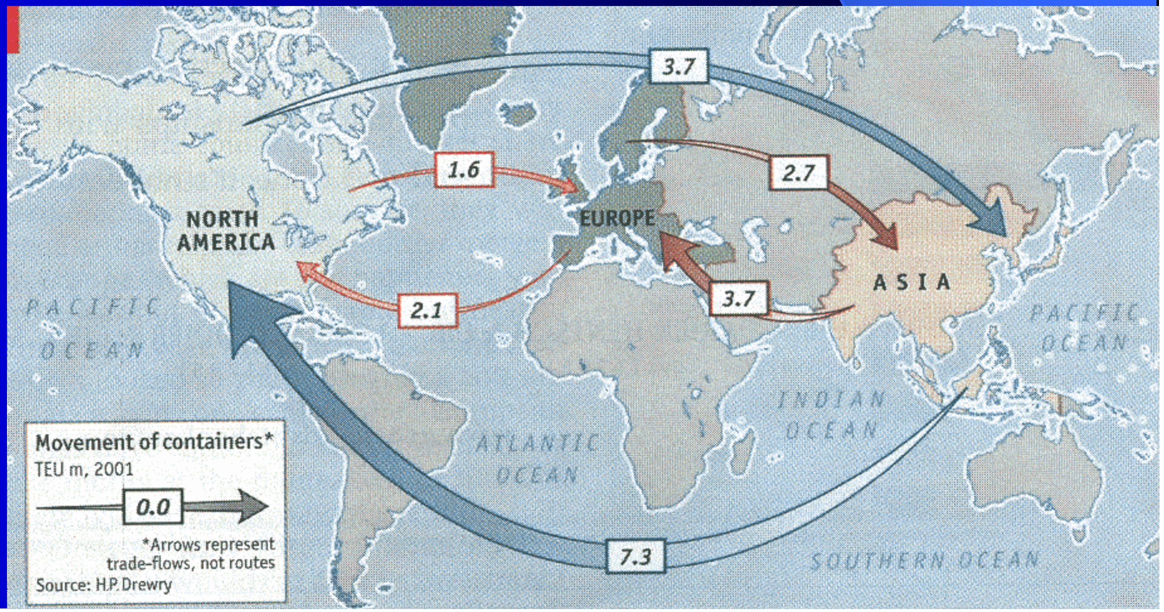
# Detection of explosives in the trade system : countermeasures against illicit trafficking


The size of the container industry is enormous : in FY 2002 the world's total movement in containers amounted to about 72 M TEU ("Twenty-foot Equivalent Unit) that are transported by ships and deposited inside the harbours Customs areas.

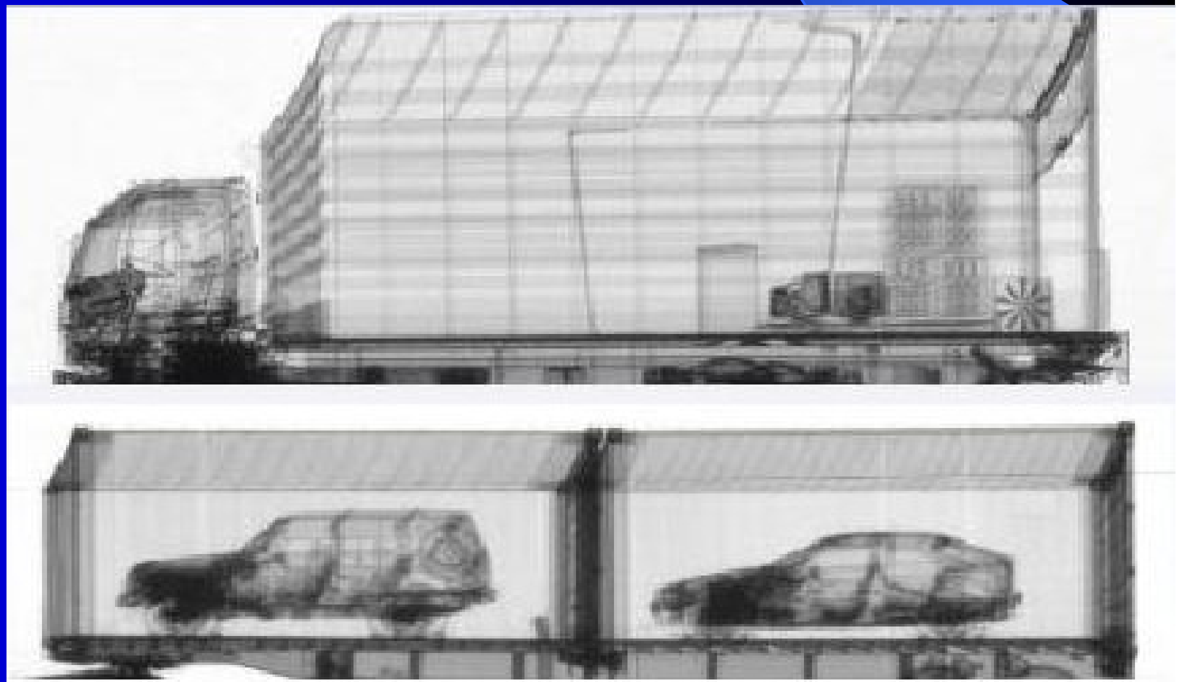
There is an increasing risk that sizeable amounts of "threat materials", including explosives, be hidden in cargo and transported by means of the standard commercial network.



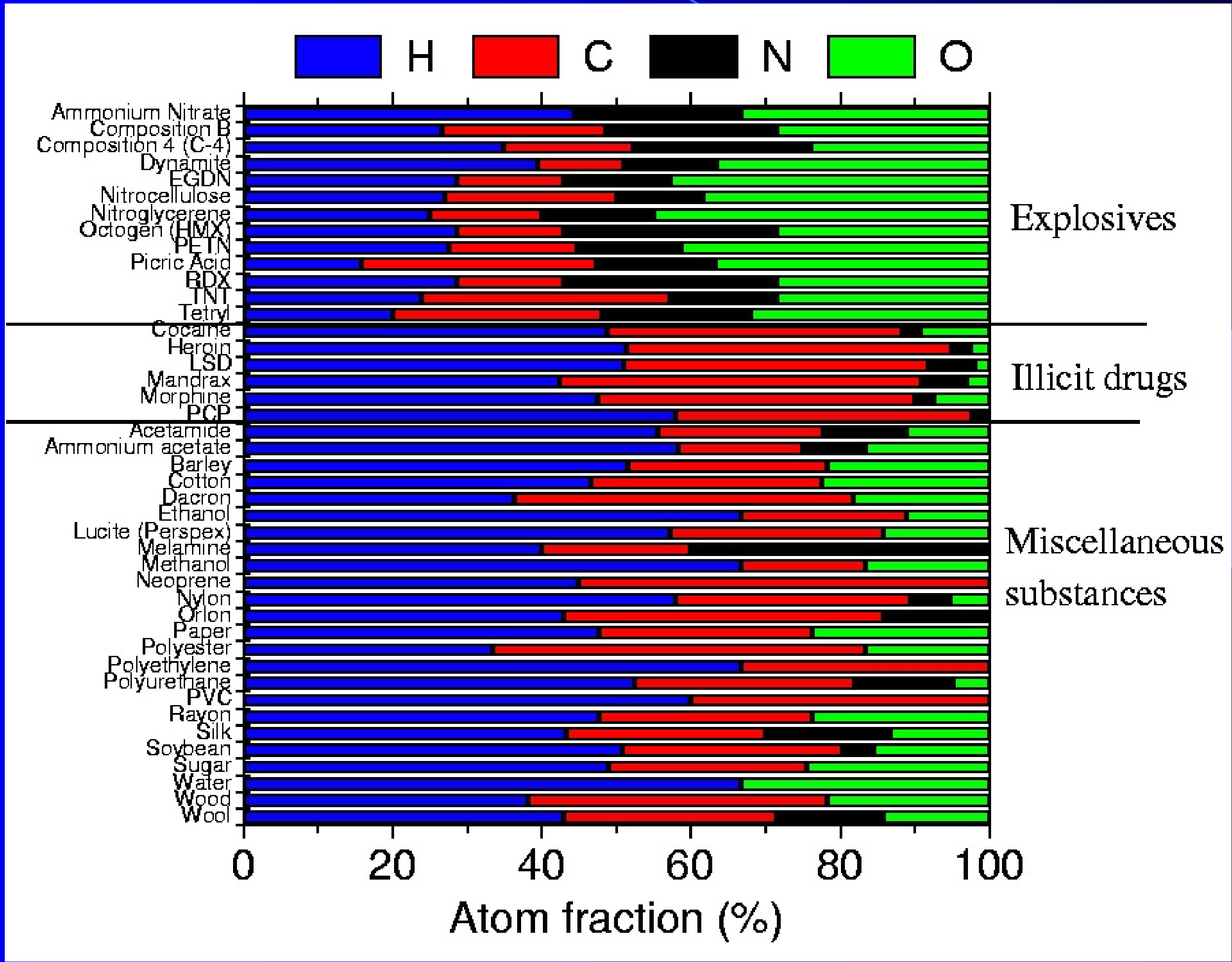
Present inspection systems at ports are based on x-ray or γ-ray radiography.

*Courtesy of SAIC, San Diego, CA, USA*

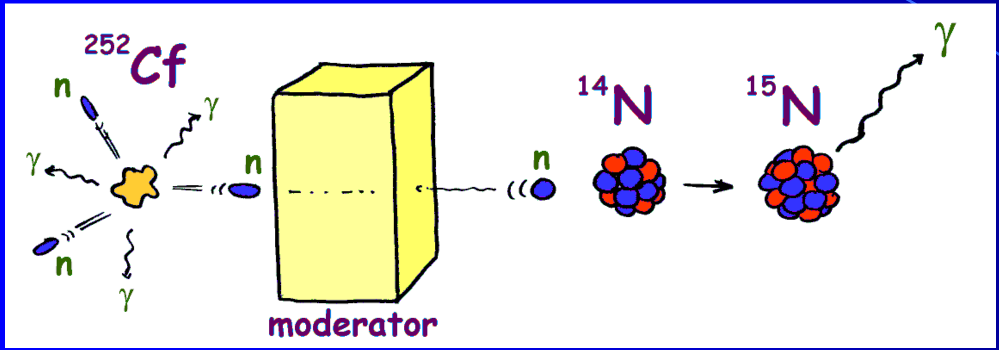
Although the pictures are rather detailed and 3D imaging is possible, the number of suspect unidentified areas is still high.



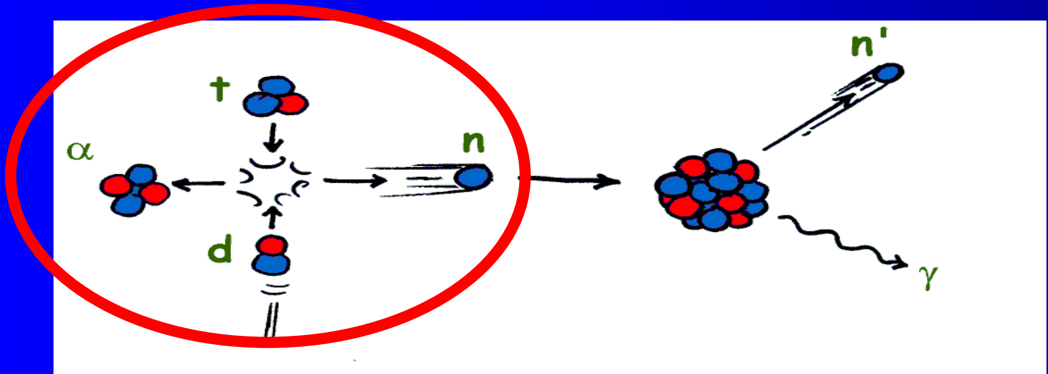
# Chemical composition of different materials



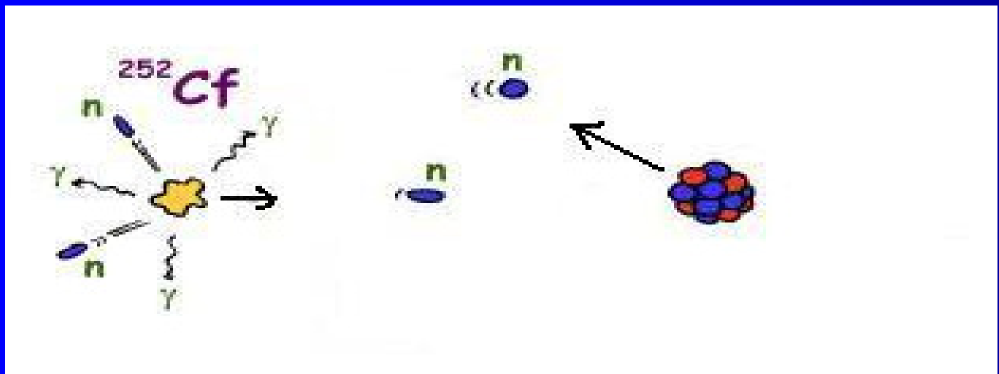
# Neutron induced reactions




Thermal neutron capture




Inelastic scattering

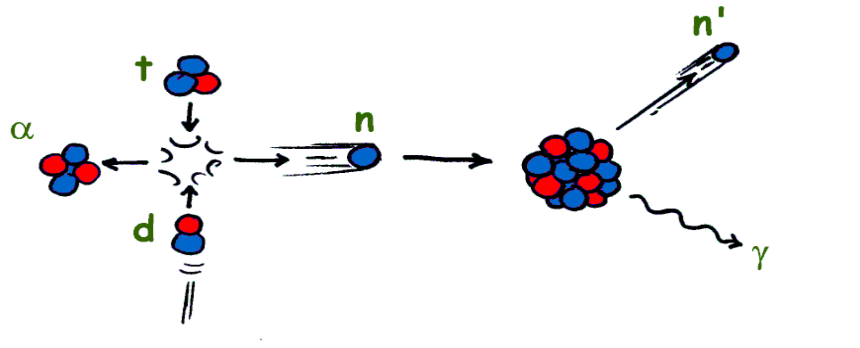


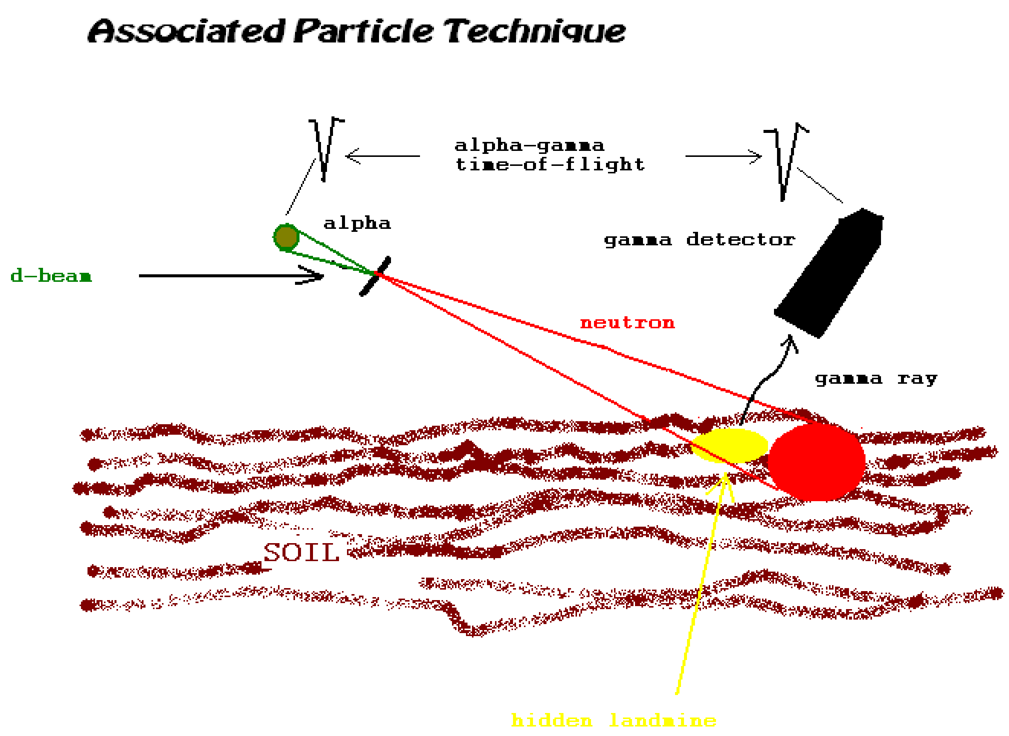

Backscattering

# γ-ray transitions of relevant elements (MeV)

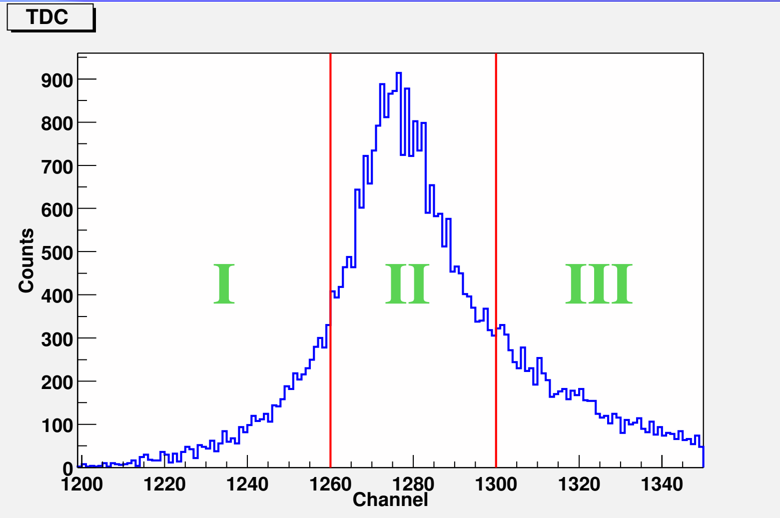
| Element | capture | inelastic |
|---|---|---|
| H | 2.2 | none |
| C | | 4.42 |
| N | 10.82 | 1.6 - 2.3 - 5.1 |
| O | | 3.8 – 6.1 |

# TNIS : Tagged Neutrons Inspection System based on the "Associated Particle Technique"



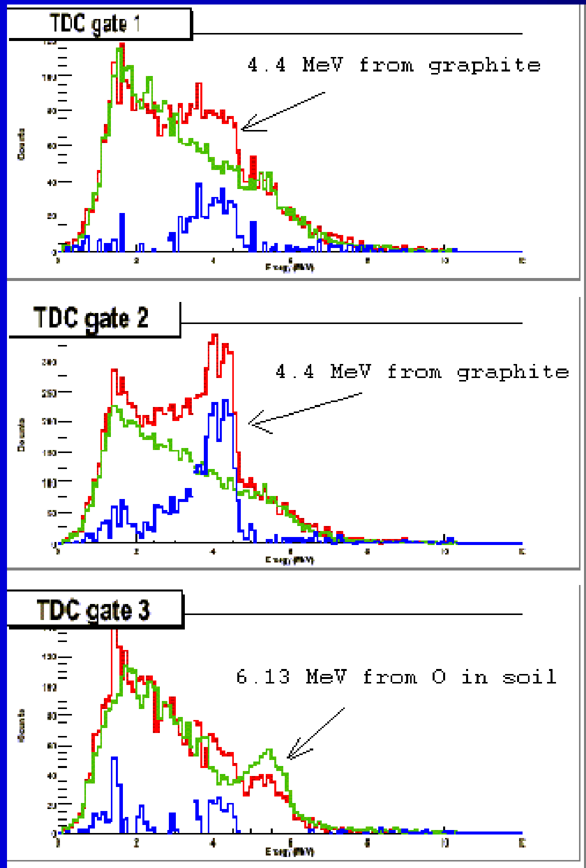



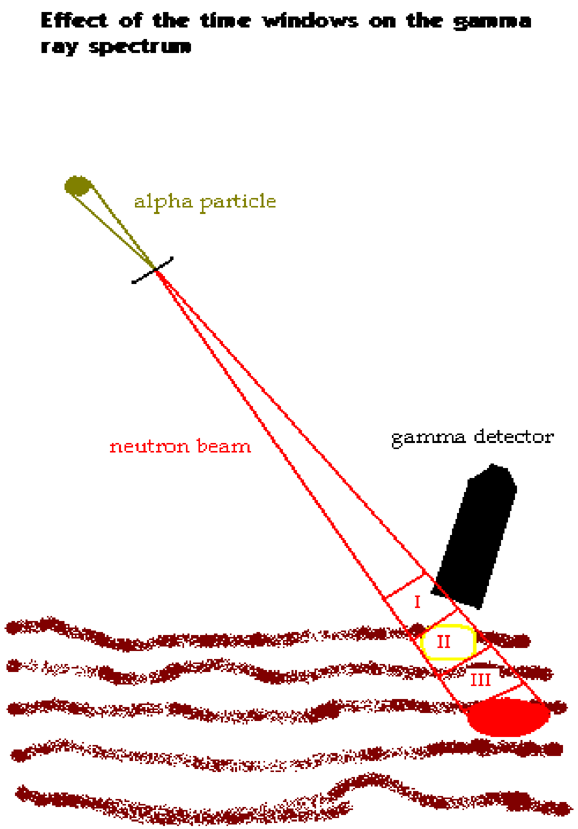

In the d + t reaction a neutron with energy of 14 MeV and an alpha particle with energy of 3.5 MeV are emitted "back-to-back" in the COM.



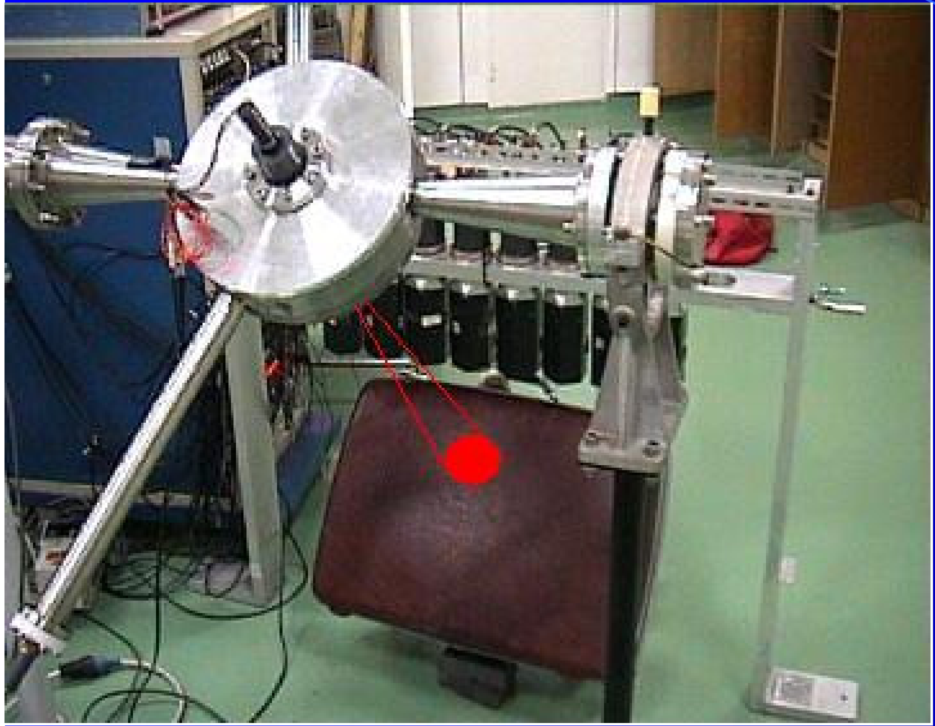

Alpha-Gamma time-of-flight and gamma energy signals are recorded and used to recognize the elemental composition of a well defined irradiated area.

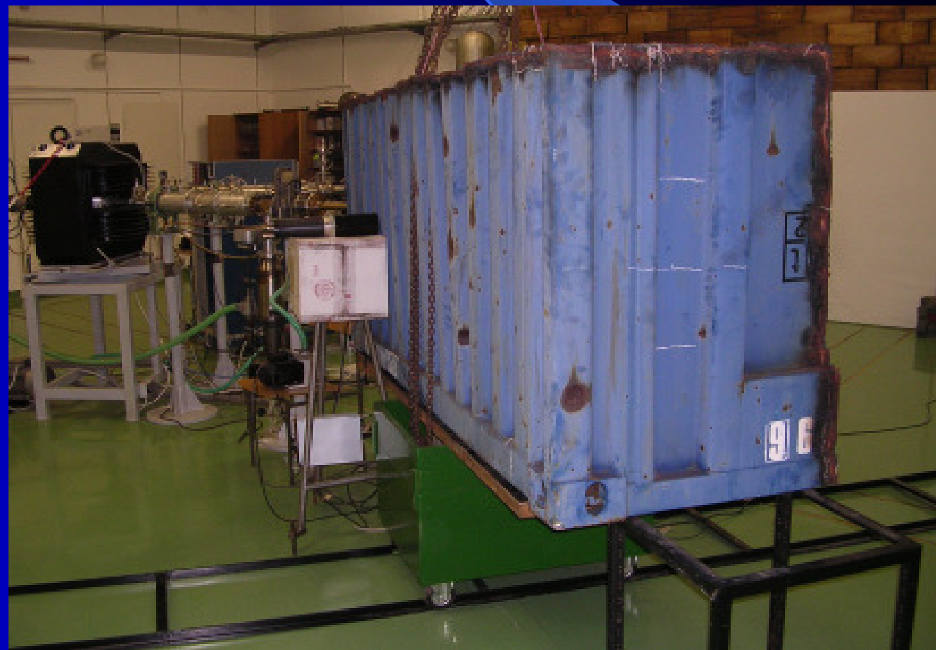
Different elements are detected in different volume cells (“voxels”) using the tagged neutron beams.



# The experimental setup at the Institute Ruder Boskovic in Zagreb (Croatia)

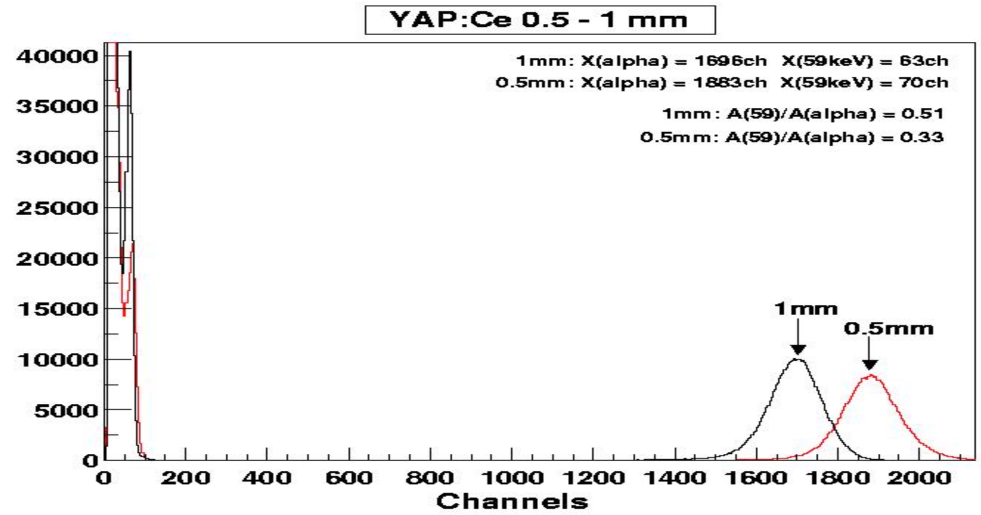


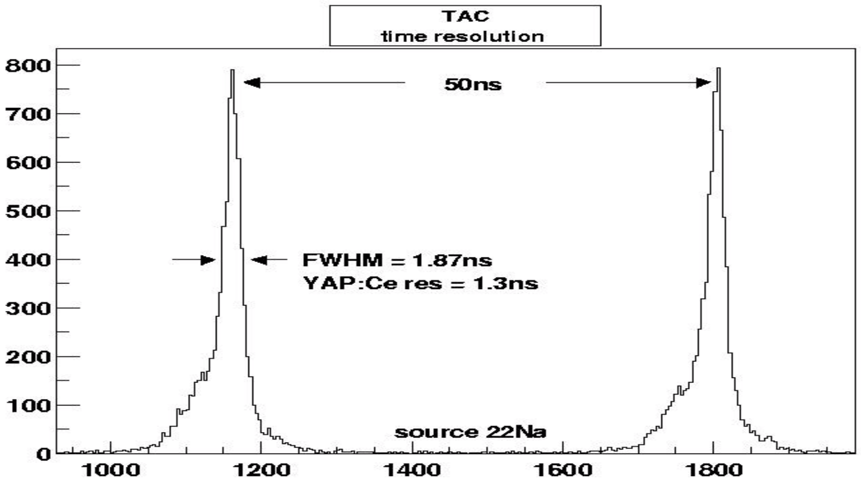


Beamlines dedicated to inspection of suitcases and containers for airport and harbour security

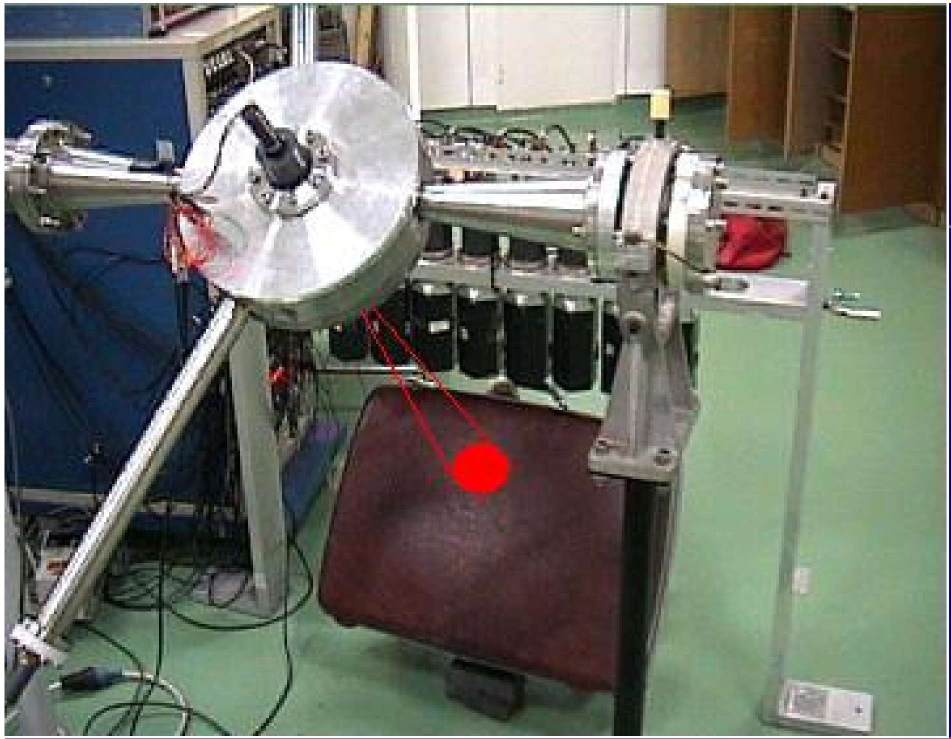
# The alpha particle detector is a YAP(Ce) crystal of 40 mm diameter and 0.5 mm thick, read out by a Hamamatsu R1450 PMT.

Energy resolution of YAP(Ce) for Eα = 5.4 MeV and Eγ = 59 KeV



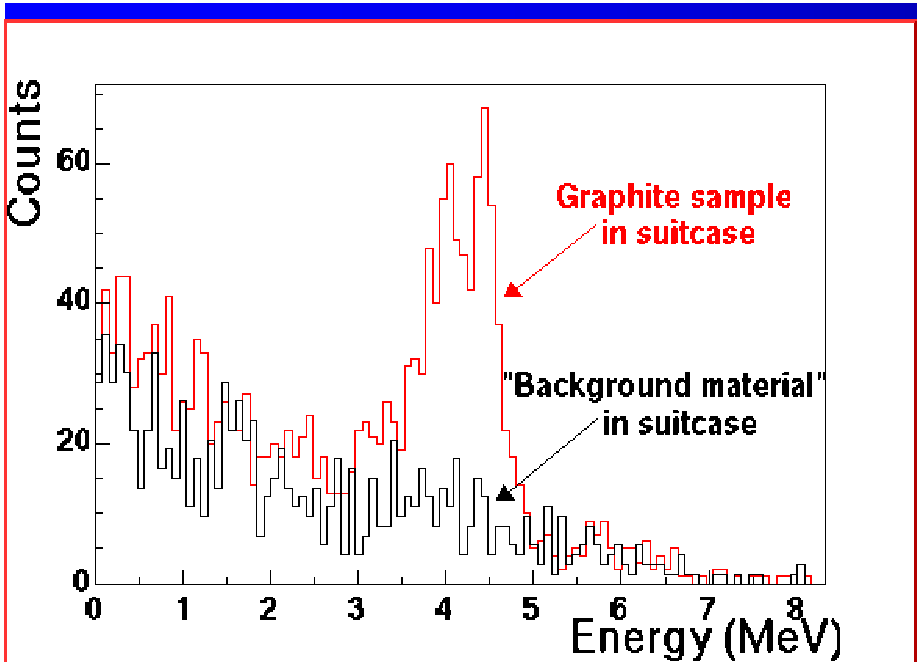

Timing resolution of two YAP(Ce) detectors for two coincident 511 KeV γ - rays

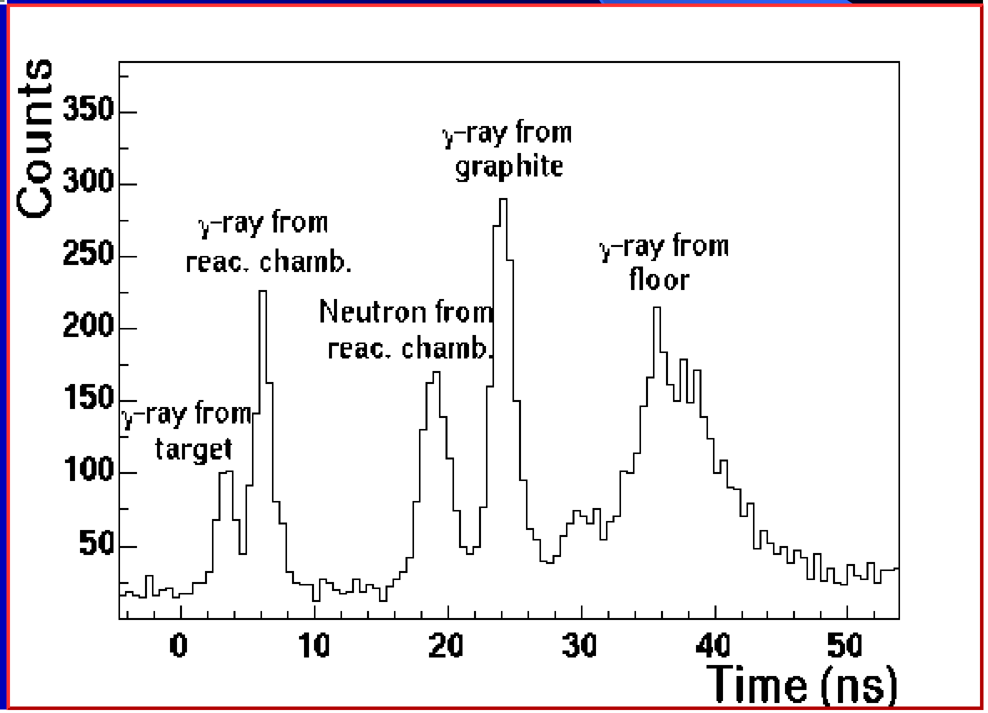


Irradiation of a 10x10x10 cm. graphite sample hidden inside the suitcase

Right : alpha-gamma timing spectrum

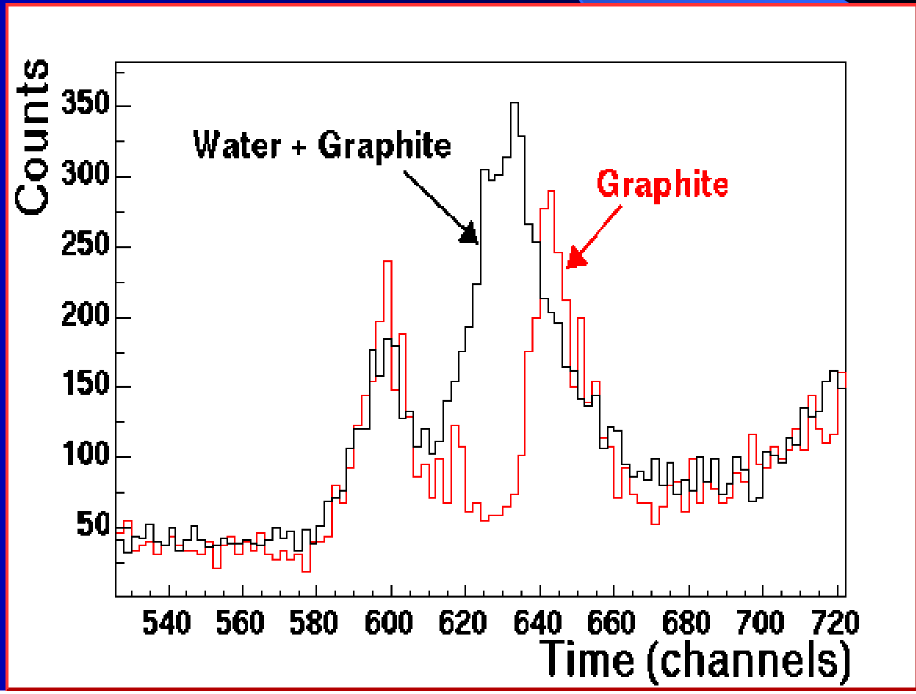
Left : gamma energy gated on the “graphite” in the timing spectrum



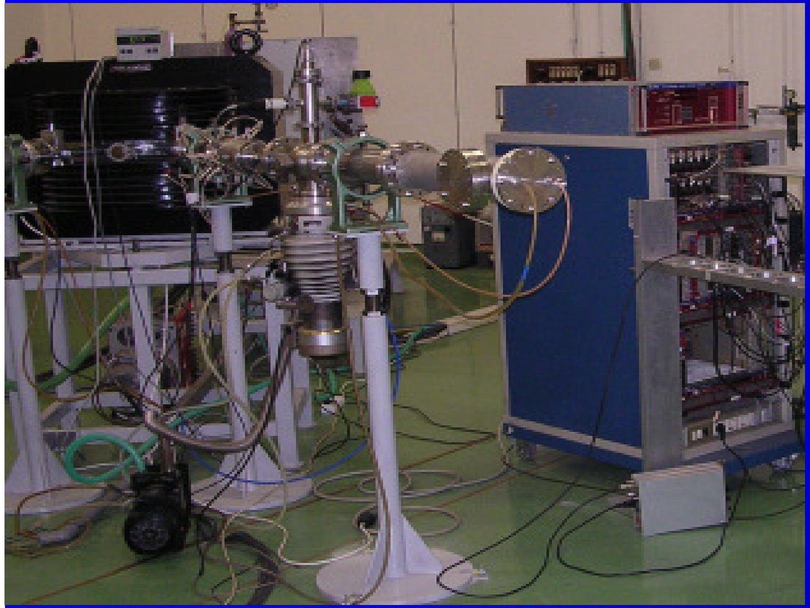



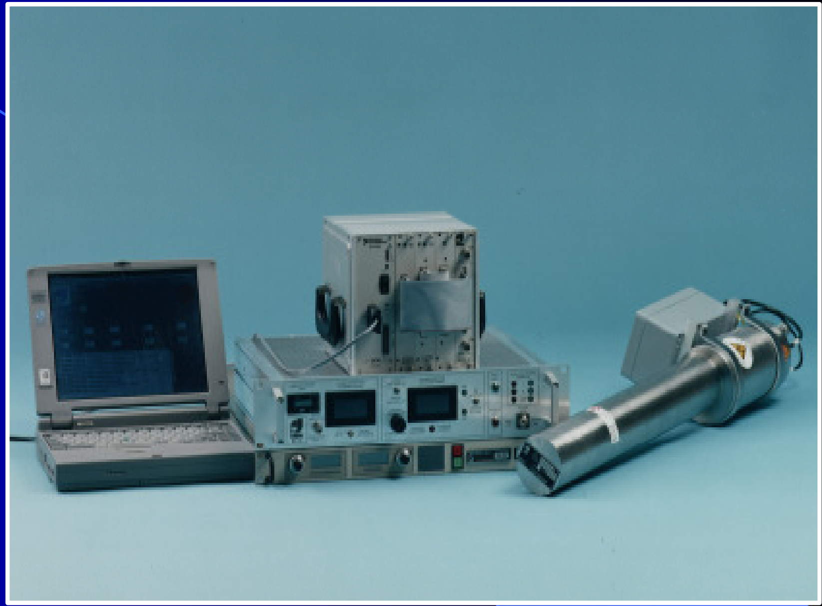
Inserting a bottle of water inside the suitcase in front of the graphite sample.

Effect of the bottle of water on the alpha-gamma timing spectrum, one can clearly see the component added at shorter time.



# Present development : a portable sealed neutron generator with the associated particle detector (TPA)

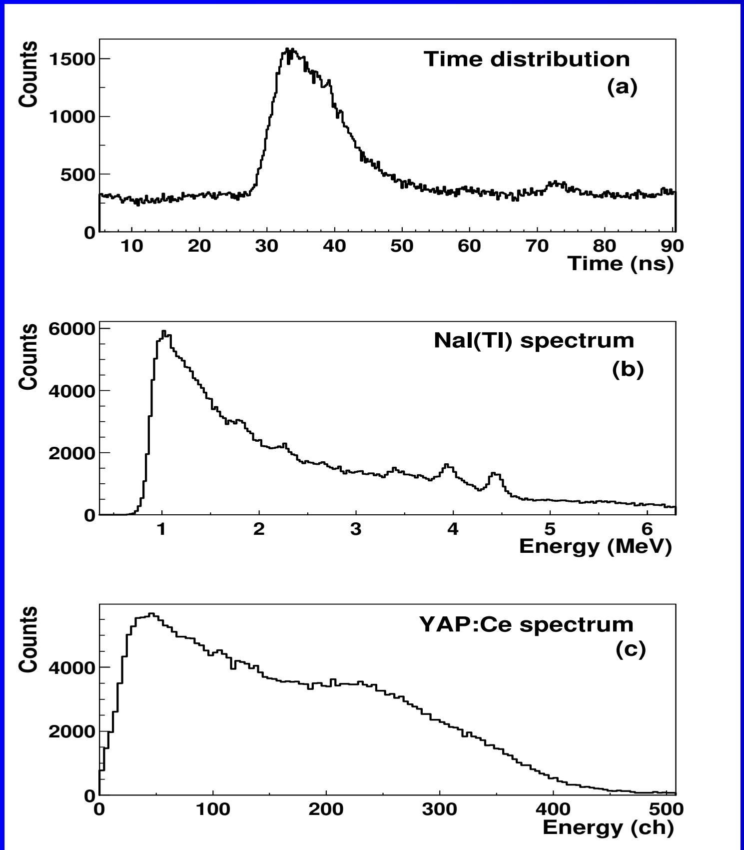


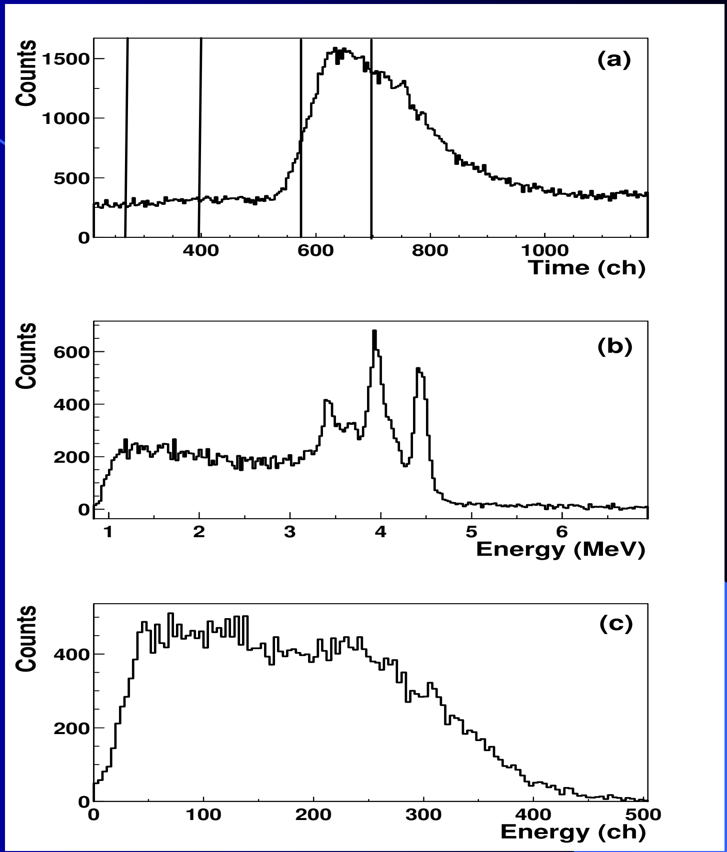


A portable sealed neutron generator capable of delivering 10exp8 neutrons/second.
Mounting the alpha particle detector inside the neutron generator.

*Courtesy of EADS-Sodern*

# First results with the TPA

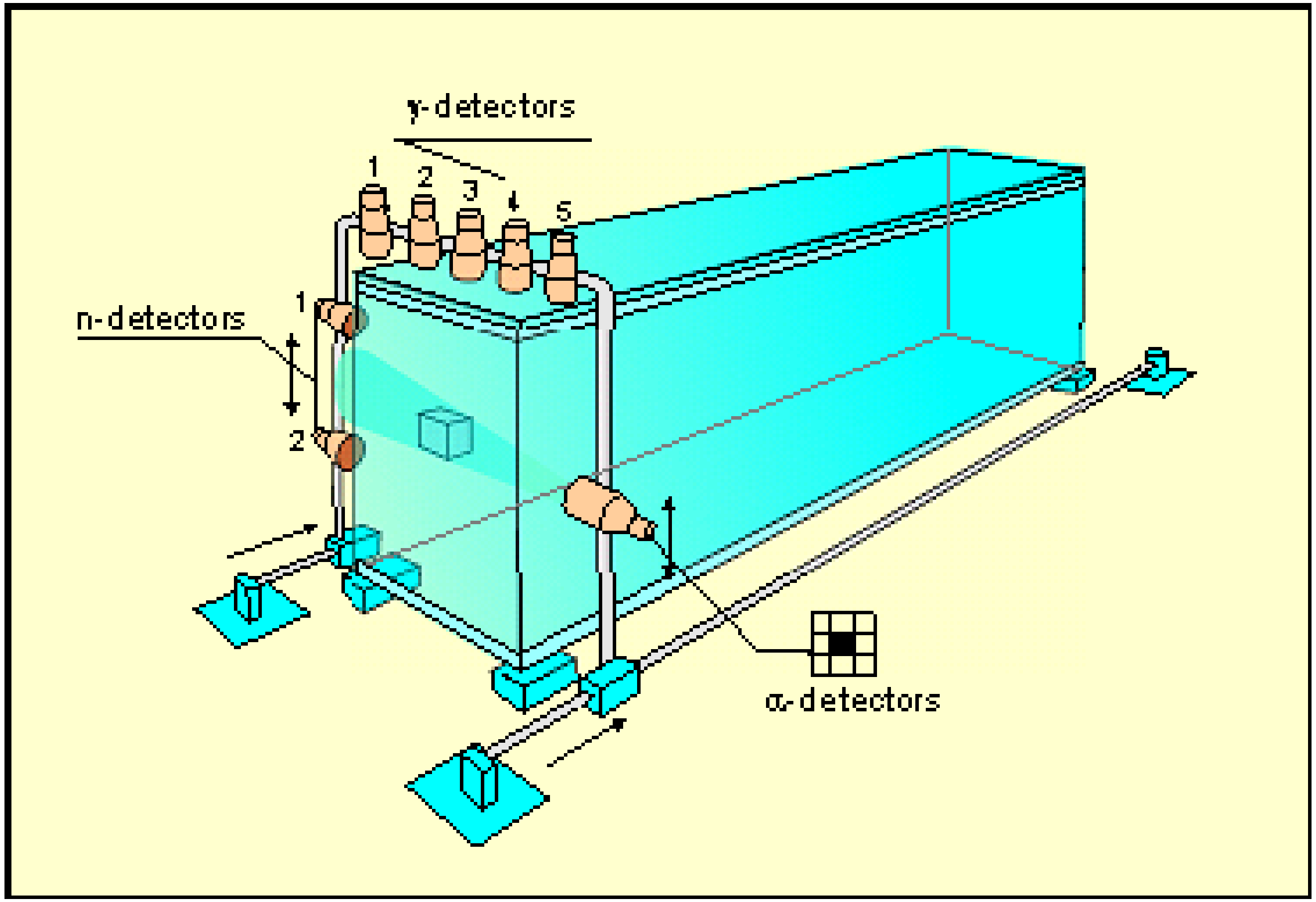



**Graphite sample irradiation spectra obtained from an NaI(TI) detector *without* "nanosecond coincidence" with the α-particle**

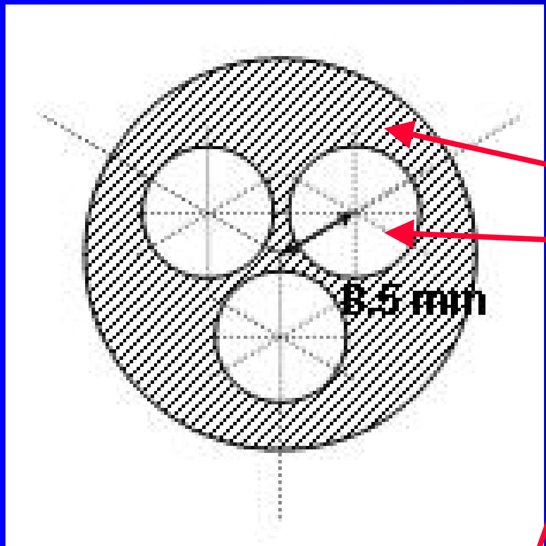
**Graphite sample irradiation spectra obtained from an NaI(TI) detector *with* a 3 nanosecond coincidence with the α-particle**

# Layout of a container inspection station



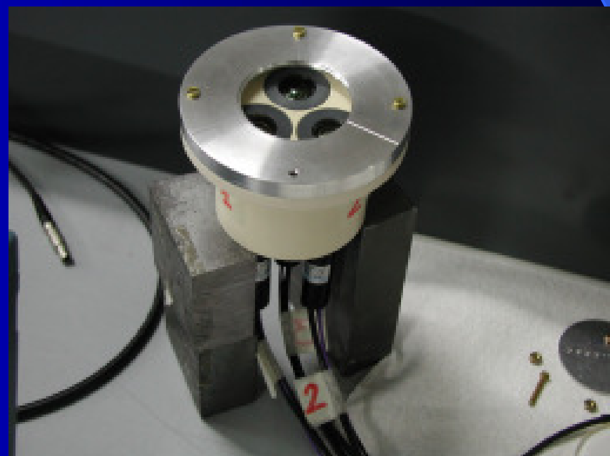

There is need for 3D position resolution !

# YAP:Ce + 3 PMT's



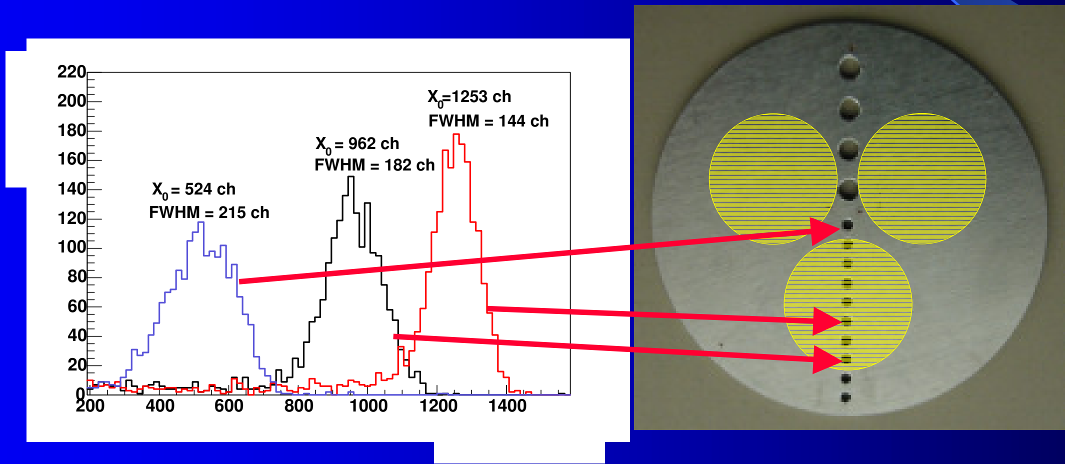

YAP:Ce detector ($\Phi$ = 40 mm, t = 0.5 mm)

read by 3 PMT's Hamamatsu R4141 ($\Phi$ = 13.5 mm)



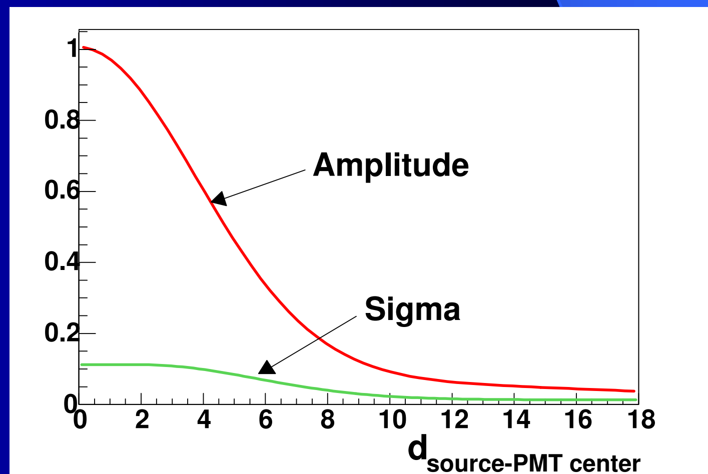
# Study of position sensitivity

$\Phi_{PMT} < \Phi_{YAP:Ce}$ => the light collection efficiency depends on the relative position of the alpha particles hitting the detector surface with respect to the PMT center ($d_{source\text{-}PMT}$)




Assumption: Gaussian pulse height distributions dependent only on $d_{source\text{-}PMT}$

Parameterization of the amplitude and width values as a function of $d_{source\text{-}PMT}$

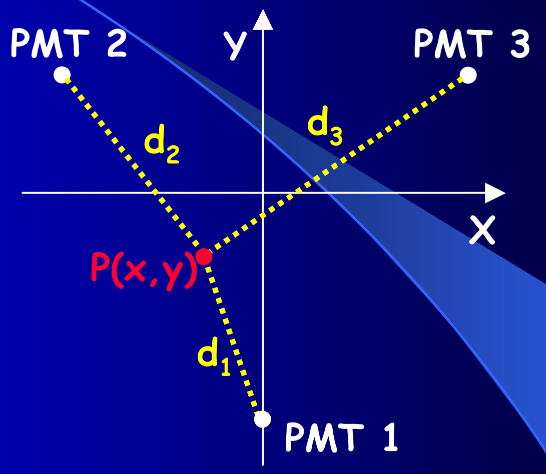


# Reconstruction algorithm

$P_i^{calc}: (A_{i1}^{calc}, A_{i2}^{calc}, A_{i3}^{calc})$

$(\sigma_{i1}^{calc}, \sigma_{i2}^{calc}, \sigma_{i3}^{calc})$

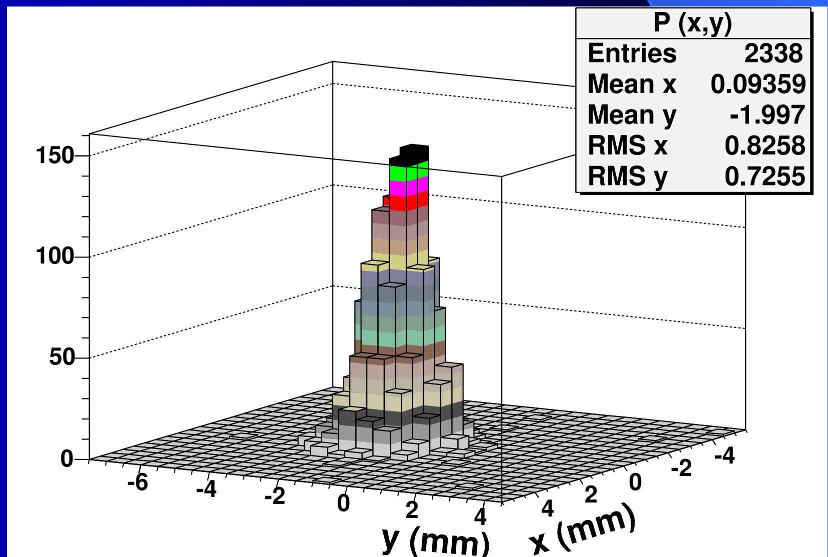
$P^{exp}: (A_1^{exp}, A_2^{exp}, A_3^{exp})$



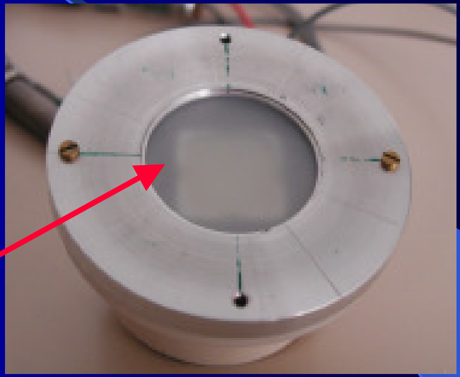

$$f(x,y) = \sum_{i=1}^{3} \left( \frac{A_i^{exp} - A_i^{calc}(x,y)}{\sigma_i^{calc}(x,y)} \right)^2$$

Looking for the coordinates that minimize the function $f(x,y)$

$(x_{rec}, y_{rec})$

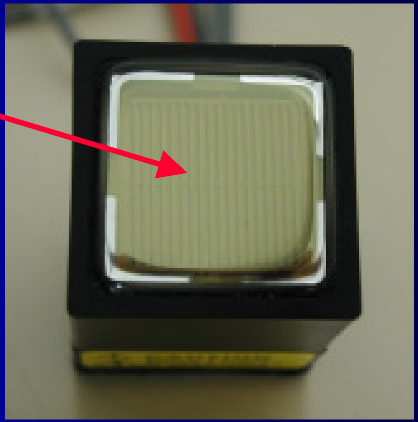


# YAP:Ce + multi-anode PMT



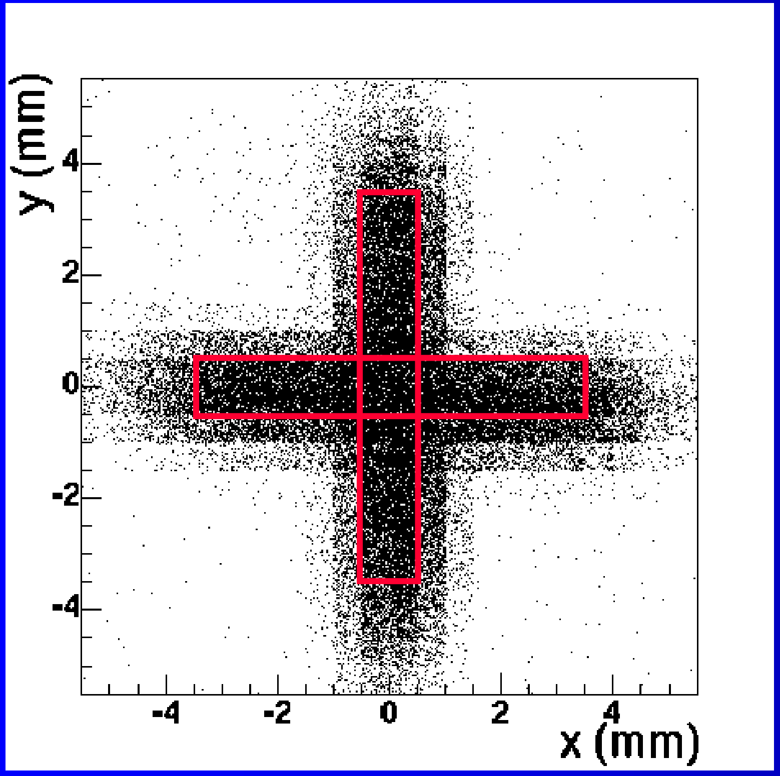
YAP:Ce detector ($\Phi$ = 40 mm, h = 0.5 mm)

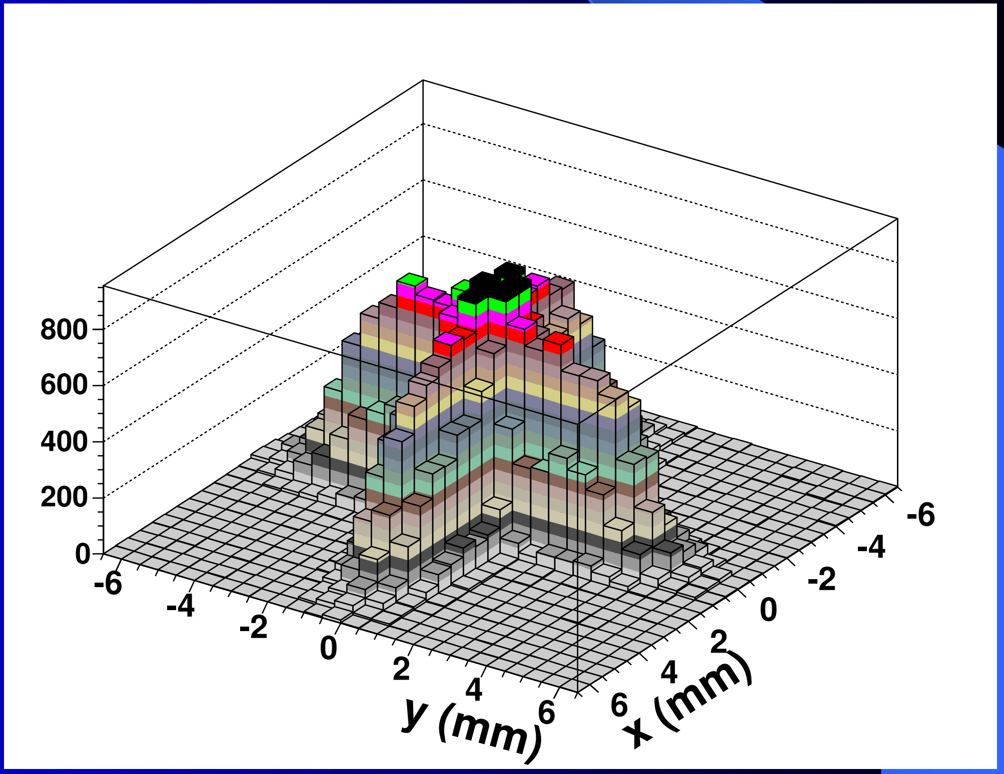
read by a 2x2 multi-anode PMT Hamamatsu R5900U-00-M4 (18x18 $mm^2$)



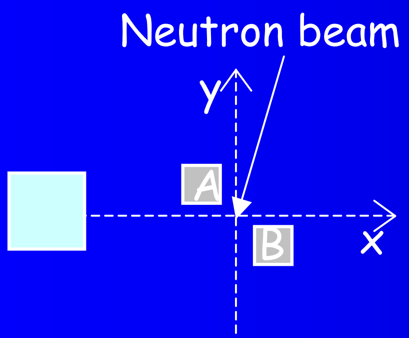
# Test with a cross collimator

Collimator with two crossed $7 \times 1$ mm$^2$ slits placed in front of the YAP:Ce detector

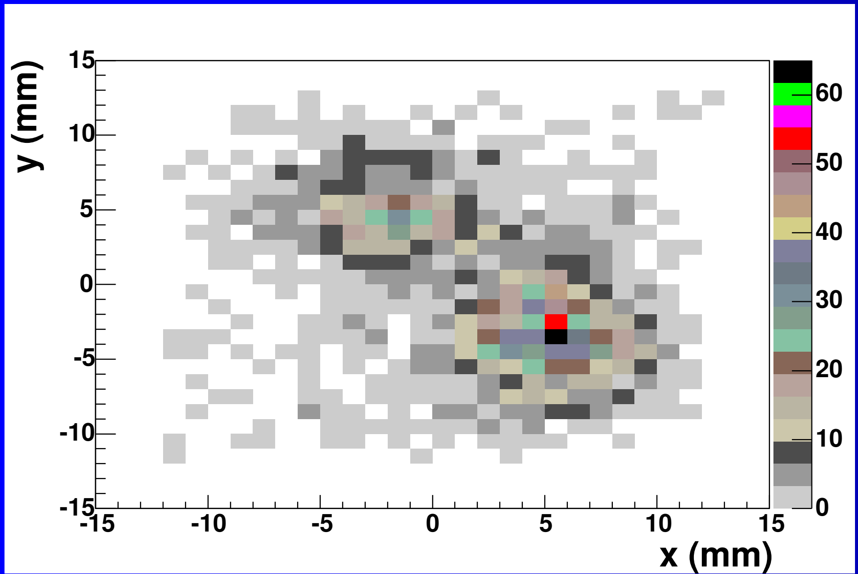


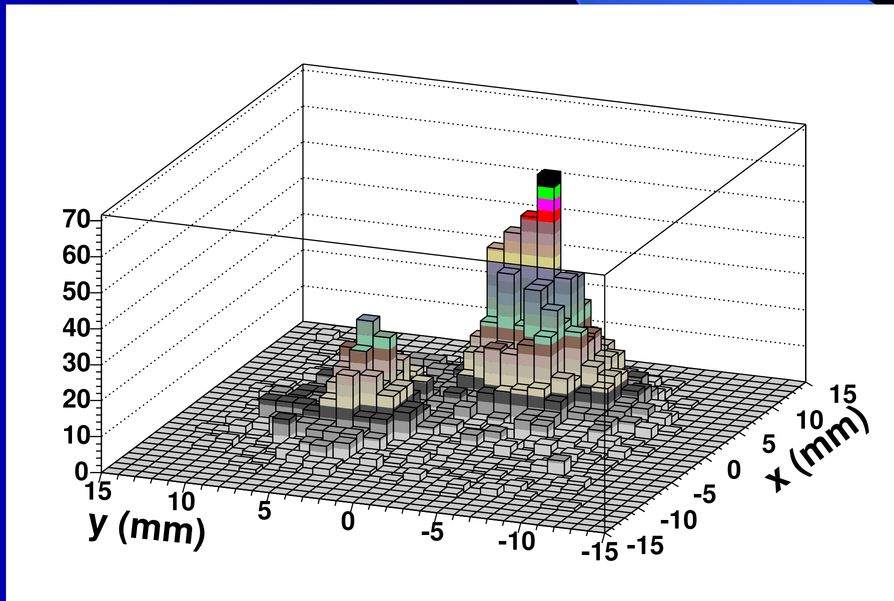



# Test with 2 graphite samples




| Sample | $x_A$ (cm) | $y_A$ (cm) | $x_{rec}$ (mm) | $y_{rec}$ (mm) |
|---|---|---|---|---|
| A | -4 | 4 | -2.0 | 4.0 |
| B | 4 | -4 | 5.2 | -3.3 |



# Results from the “Center of Gravity” method

**Pros:**

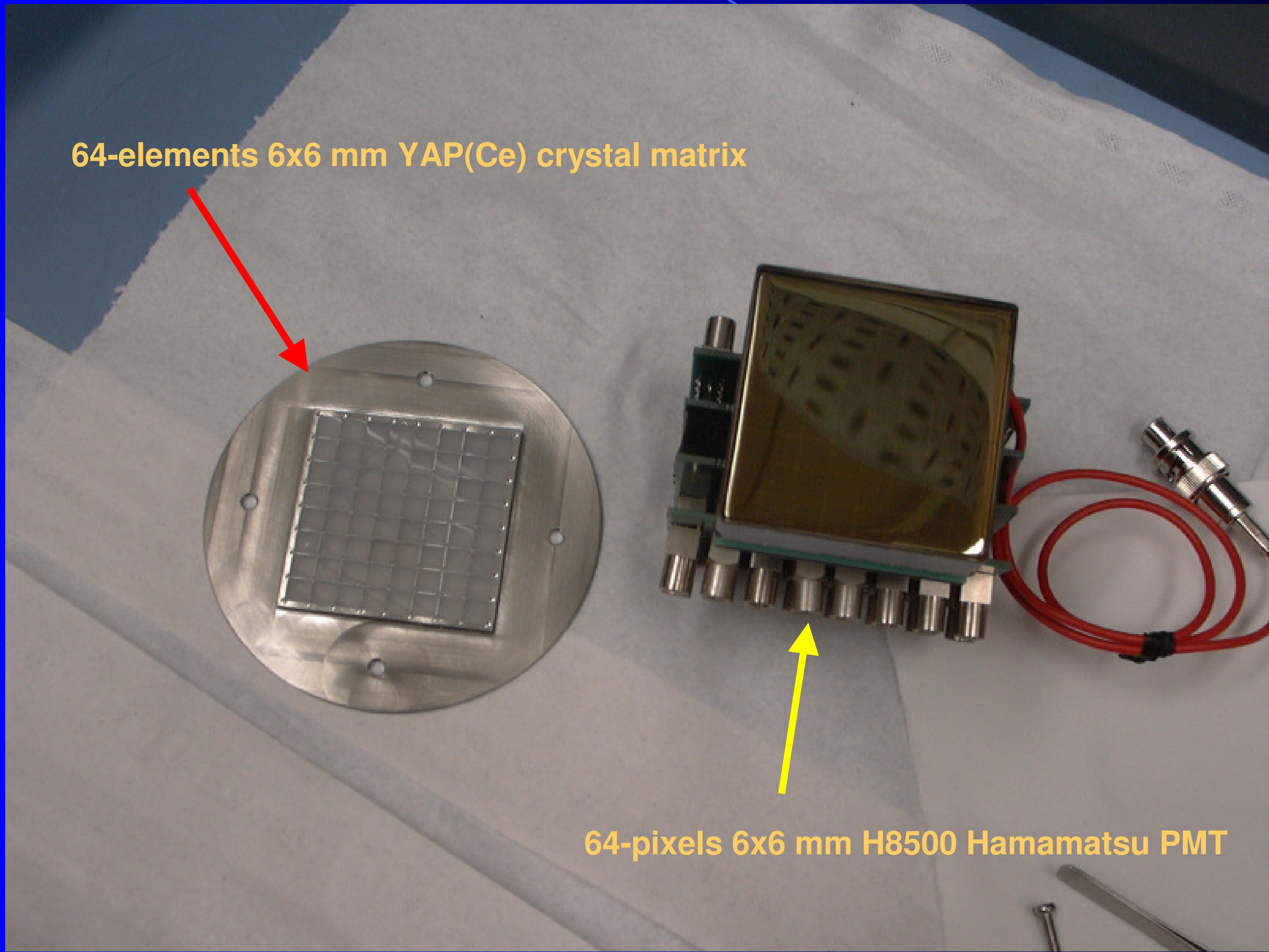
- ***Use of a single, large YAP(Ce) crystal***
- ***Position resolution of the order of 2 mm (may improve)***

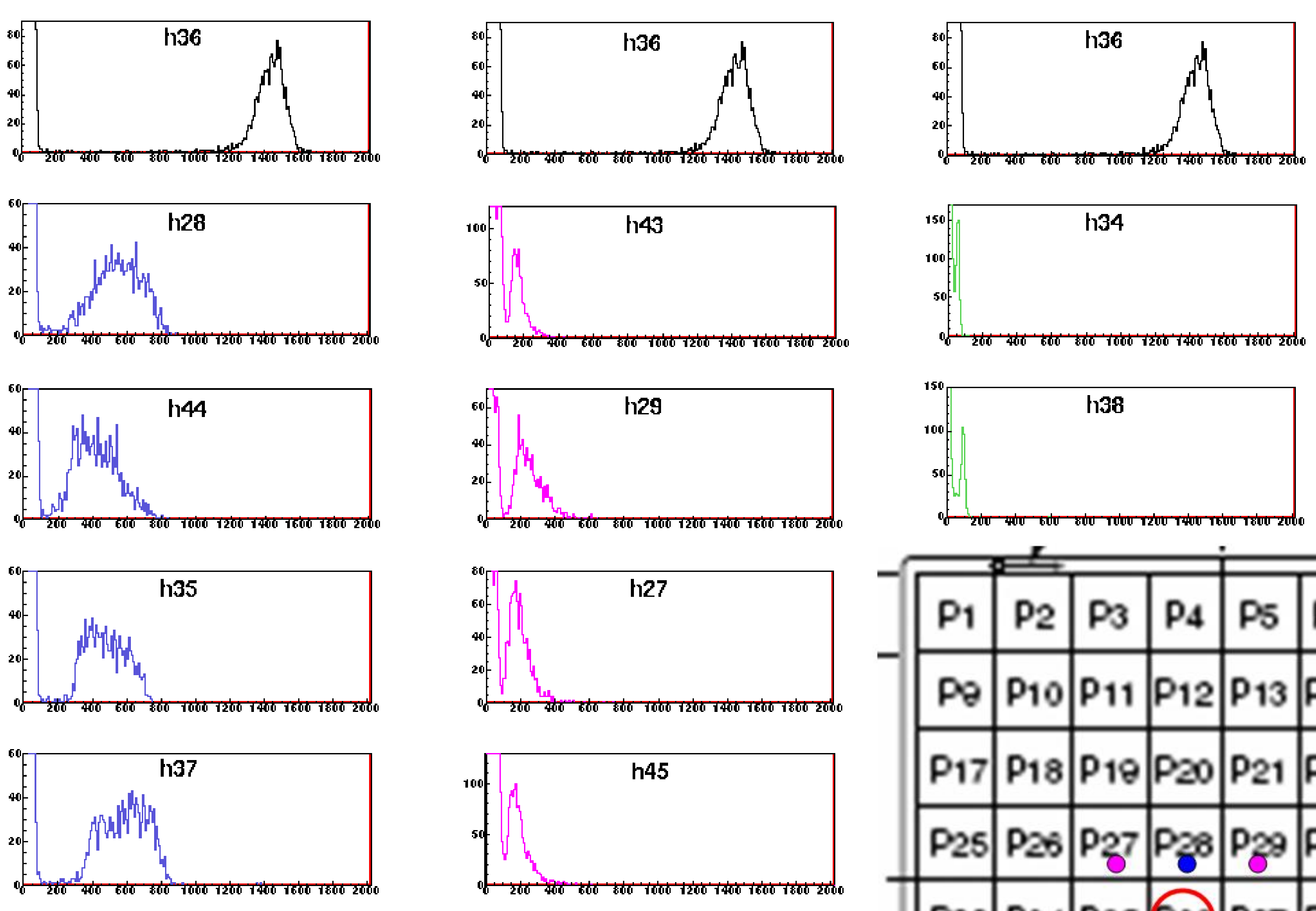
**Cons:**

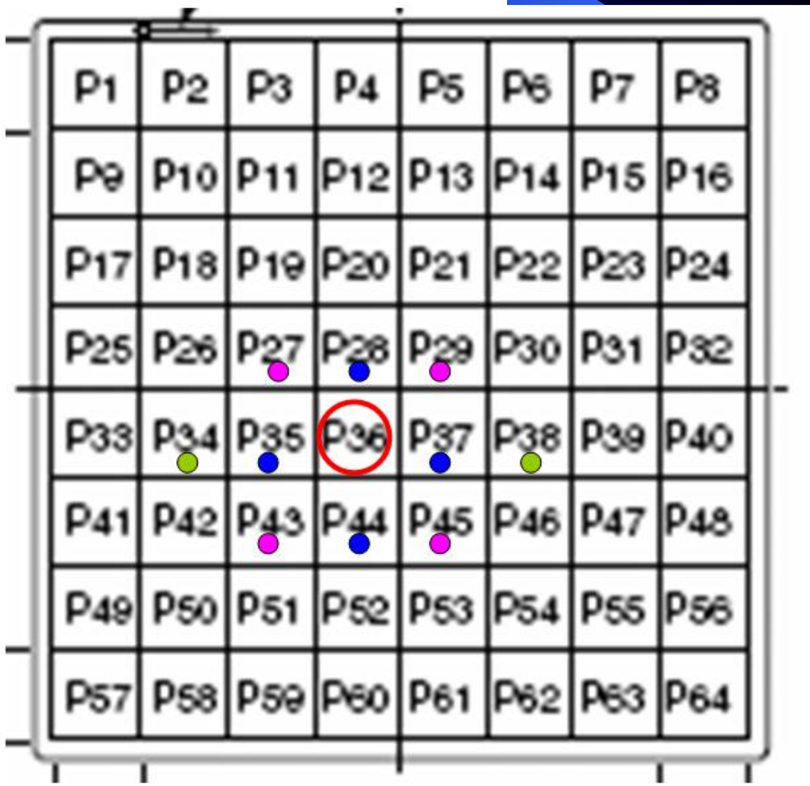
- ***Analysis of amplitude signals -> position resolution depends on precise spectroscopy of the alpha signal***
- ***Data acquisition rate of spectroscopic signal could be rather high (up to $10^7$ counts/second)***

Is it possible to achieve a suitable position resolution by simple “threshold” discrimination on the fast PMT signals ?

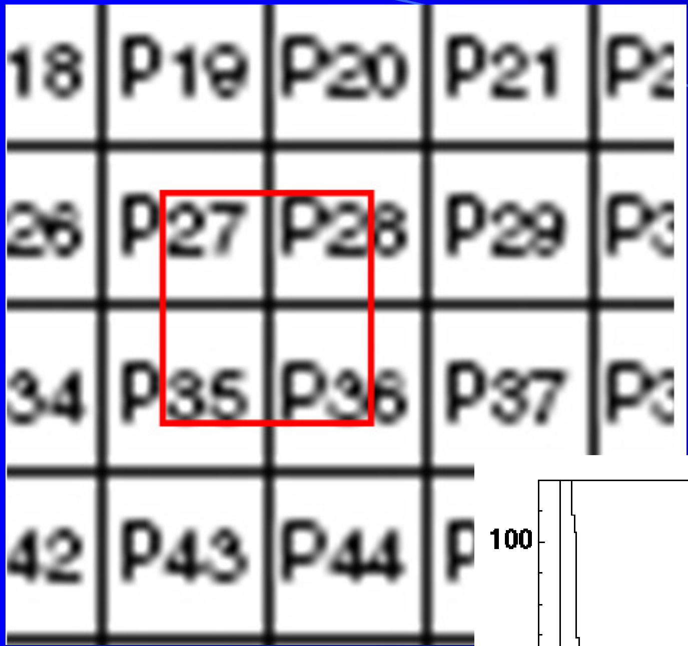
# 64-elements array “alpha tracker” setup



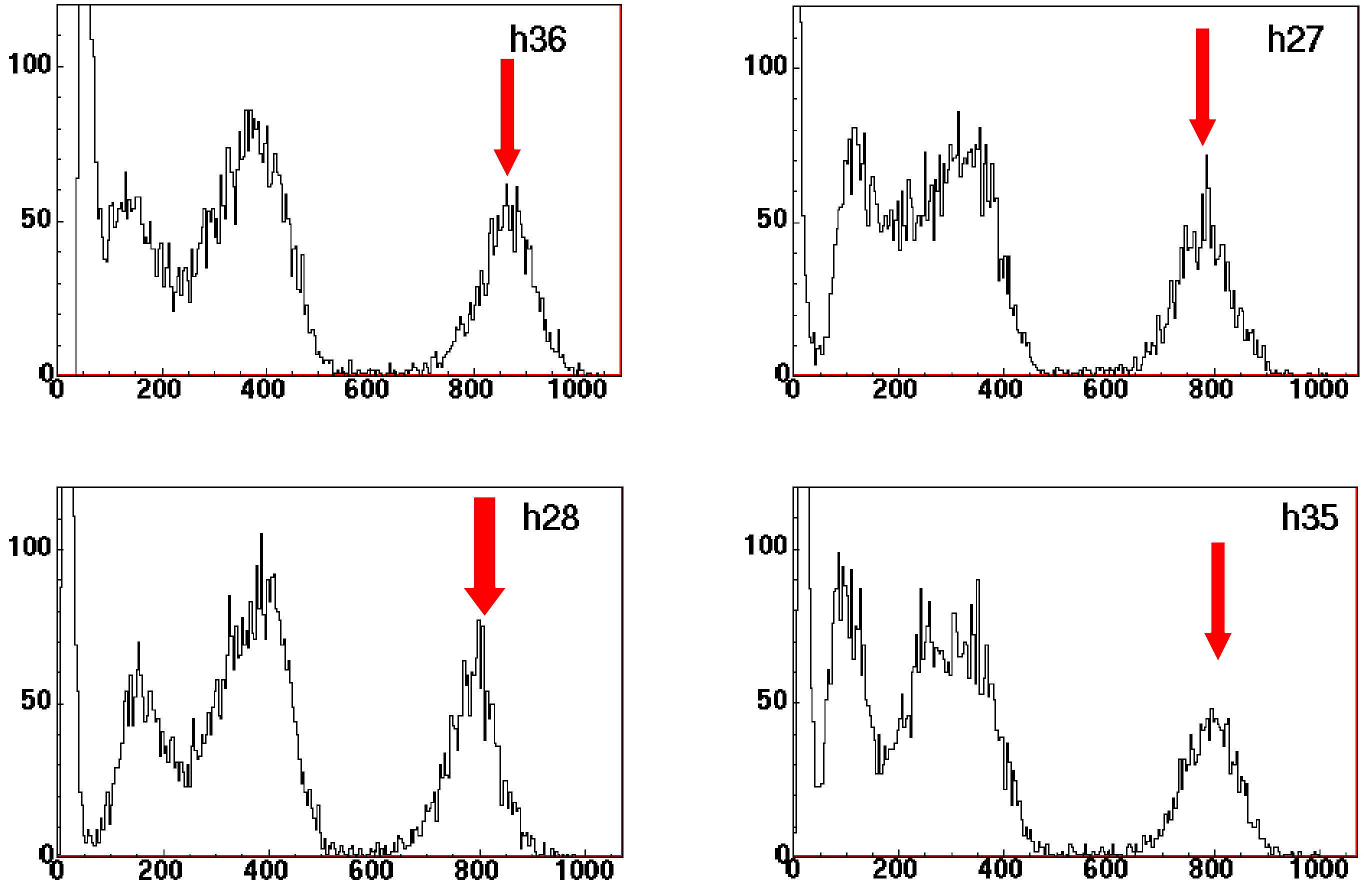


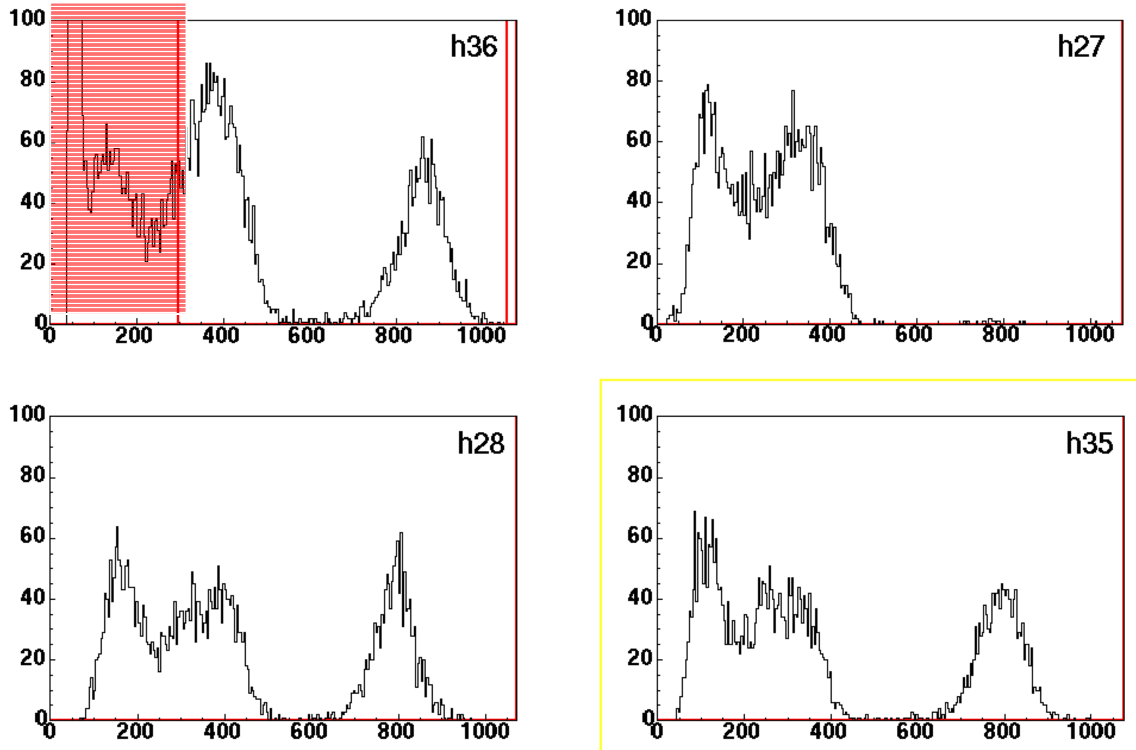




**The H8500 PMT was coupled to the matrix YAP(Ce) crystals by a 4 mm thick quartz window. The system was irradiated with an alpha source through a 2 mm pinhole collimator**




The four crystals indicated by the red square have been irradiated simultaneously through a square collimator.
The red arrows show the position of the "direct alpha hit" signal in the amplitude spectrum for each crystal.

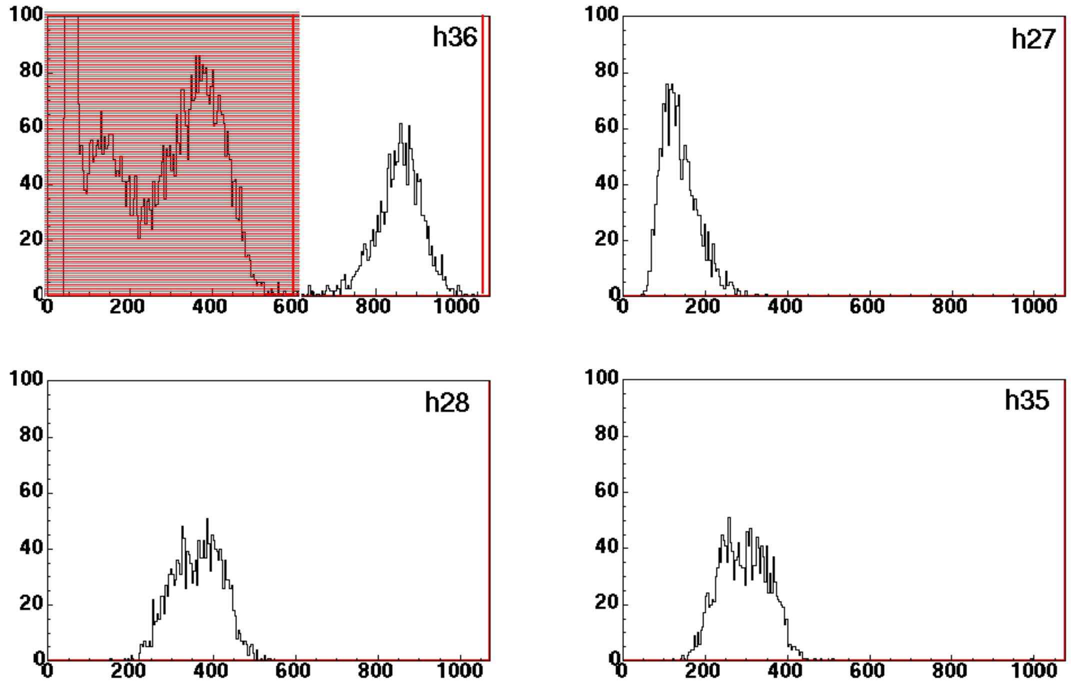





Setting a low threshold on signal #36 (pink area) results in cutting the "direct alpha hit" signal in #27 which is the farthest away.

Setting a high threshold on signal #36 results in cutting the "direct alpha hit" signals in #28 and #35 which are adjacent to #36.

In the response amplitude spectra of all crystals (pixels) the signal from "direct alpha hit" and from hits on adjacent crystals are totally decoupled.
In this configuration one can use the "threshold" to determine position



# Conclusions:

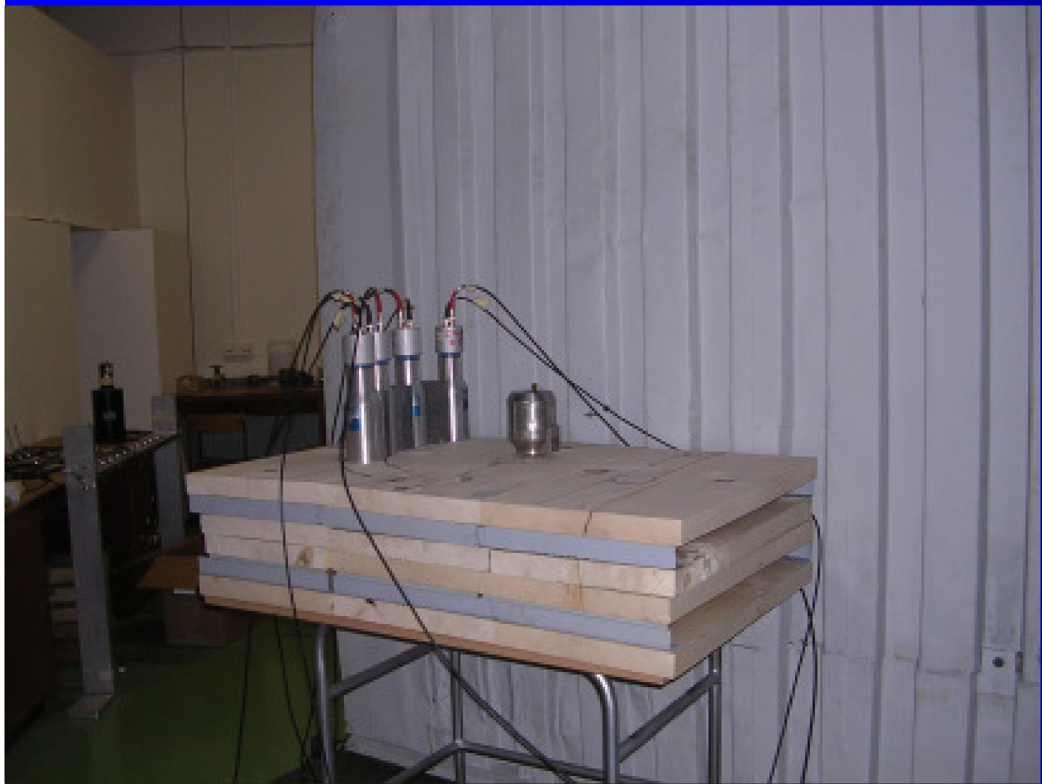
- The use of the "associated particle technique" to tag 14 MeV neutrons for inspection of cargo improves the quality of the $\gamma$-ray spectra largely reducing the background (up to a factor 50)

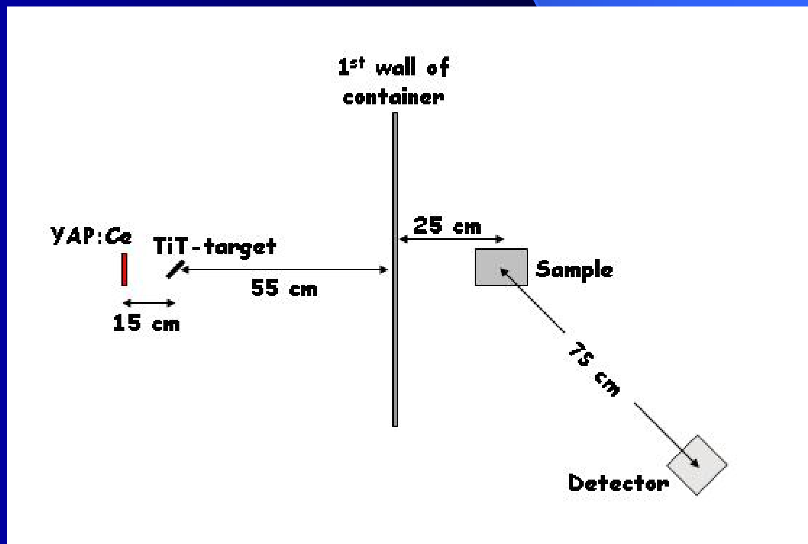
- Inspection of large items with miscellaneous loads (like a maritime container) requires the identification of a suitable size "voxel" to be irradiated

- The use of YAP(Ce) scintillators as alpha particle detectors for the tagging system is fully compatible with a sealed neutron generator

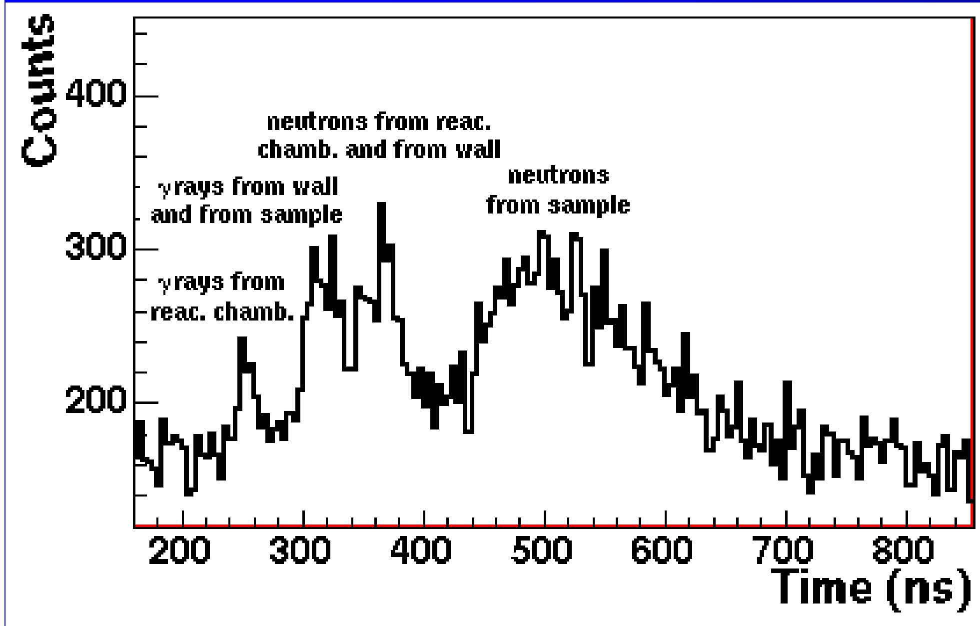
- It is possible to reach a "voxel" size of about 30x30x30 $cm^3$ in any location inside a container using an array of small crystals coupled to a suitable position sensitive PMT

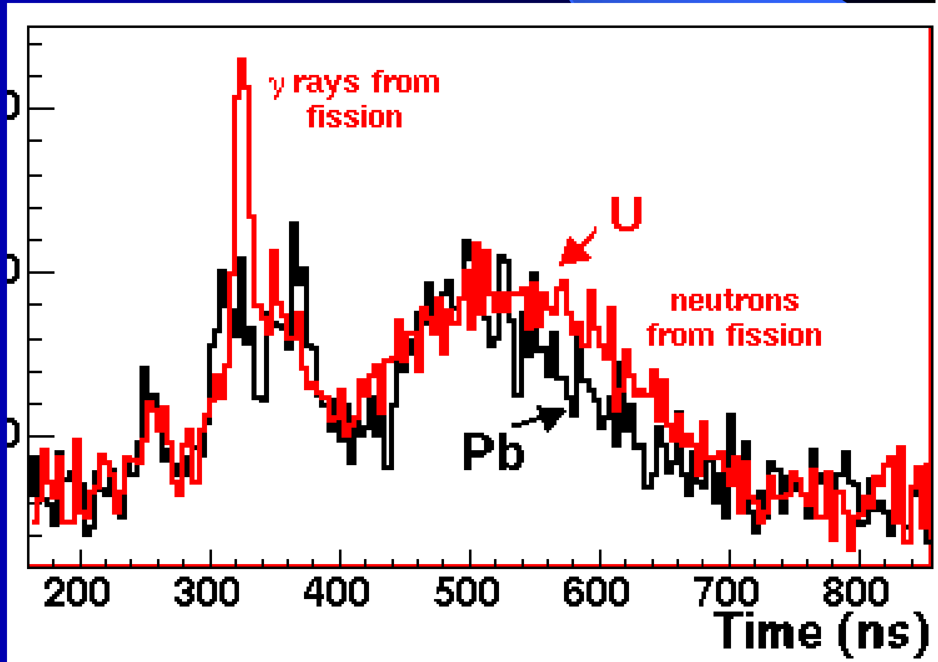
# First test on the detection of fissile material





# TOF spectra for Pb and DU



# Time of Flight spectra with γ–γ coincidences

Three different samples with the same weight have been irradiated for few minutes. Alpha-gamma-gamma triple coincidences have been recorded. In the Iron and Lead case one sees a very small of coincidences due to the detection of gammas in cascade. In the DU case one can notice the increase of coincidences due to the high multiplicity of fission fragment gamma decay.