From MACACO to MACACO II: a Compton telescope for hadron therapy treatment monitoring.

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IRIS Group: Image **R**econstruction, **I**nstrumentation and **S**imulations for Medical Imaging

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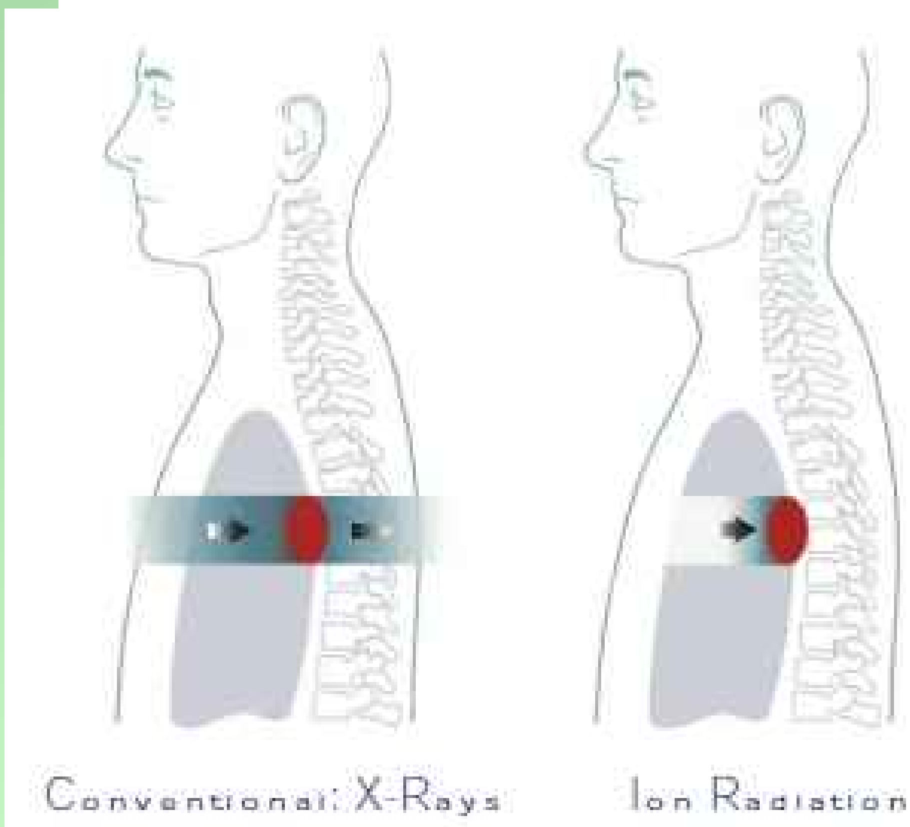
Outline

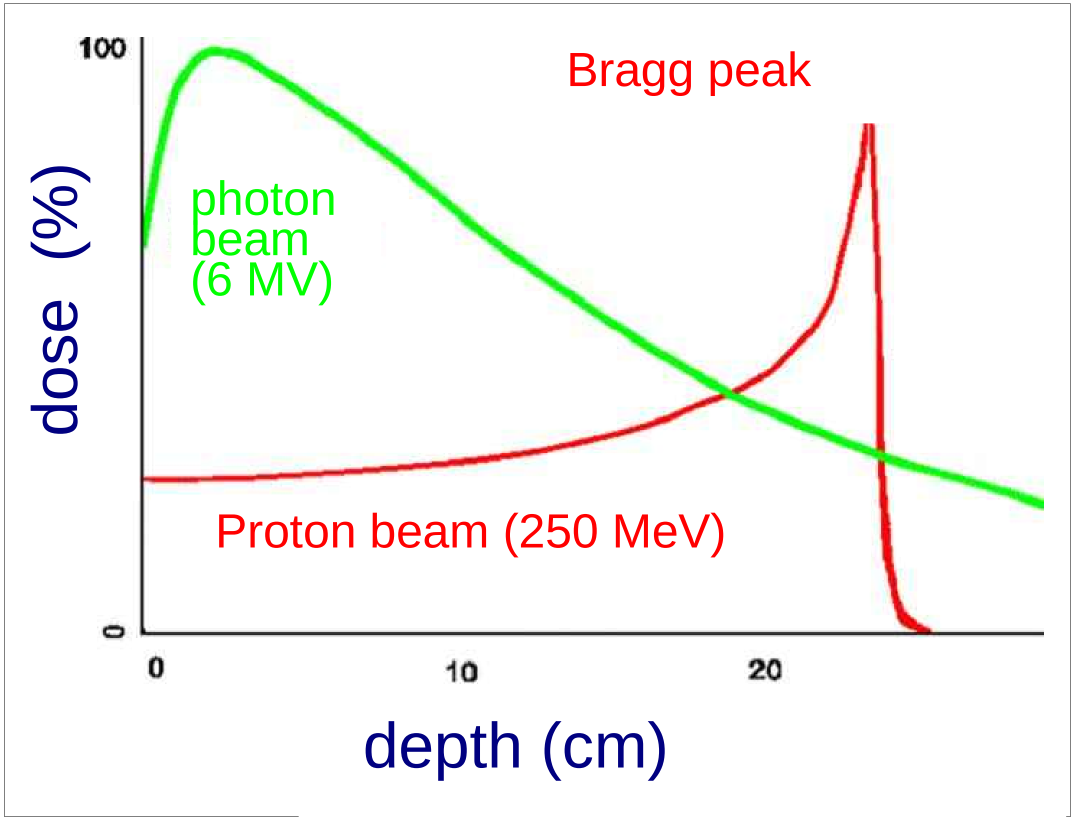
- Introduction to hadron / particle / ion beam therapy.
- Hadron therapy monitoring.
- Compton camera.
- Compton telescope @ IFIC/IFIMED
  - Final results with MACACO
  - First results with MACACO II

MACACO: **M**edical **A**pplications **C**omp**A**ct **CO**mpton camera

Hadron therapy

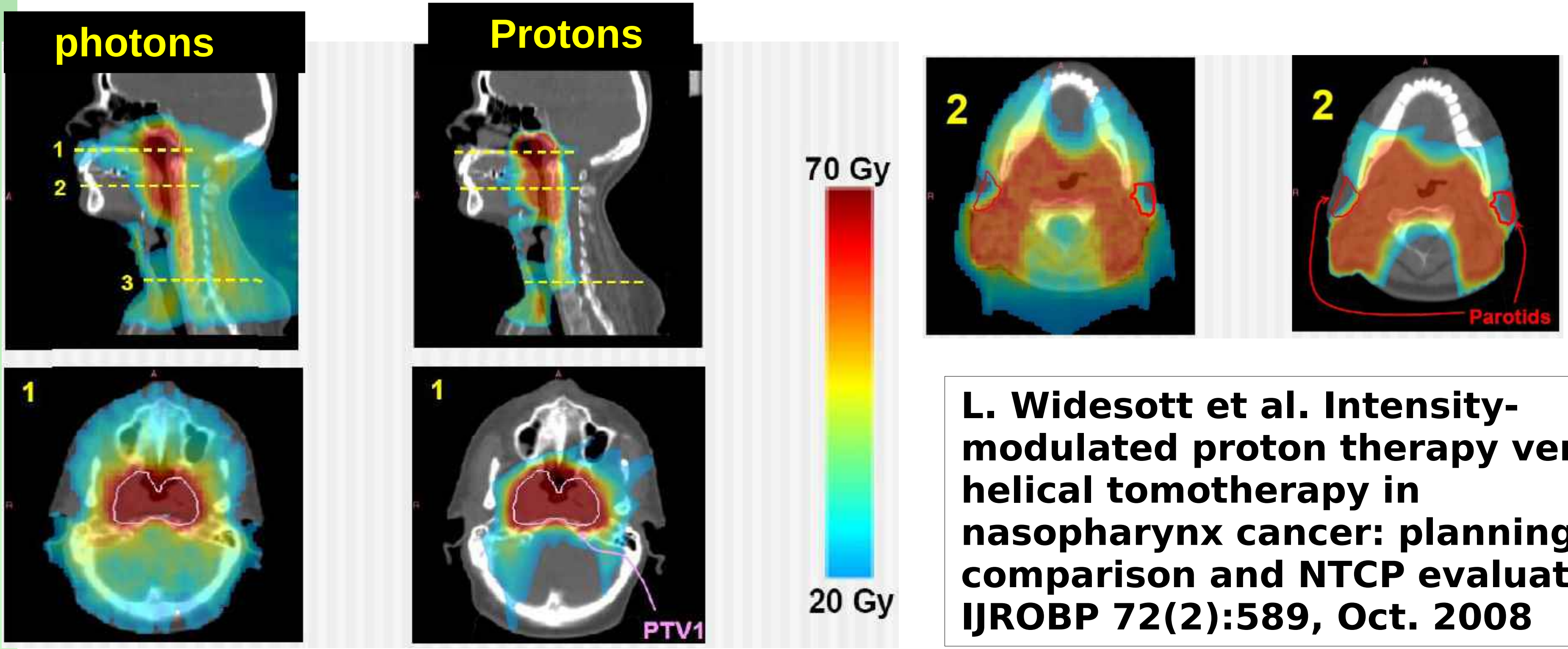
- Charged particles (protons or carbon ions) instead of photons.





Advantages

- Precise delivery to tumour area => increase of cure rates and **reduction of side and long term effects** and secondary cancer.
- Higher relative biological effectiveness (RBE) than photons.
- Large benefit over conventional radiation therapies in some cases (ocular tumours, children, organs at risk, radioresistant tumours).



L. Widesott et al. Intensity-modulated proton therapy versus helical tomotherapy in nasopharynx cancer: planning comparison and NTCP evaluation. IJROBP 72(2):589, Oct. 2008

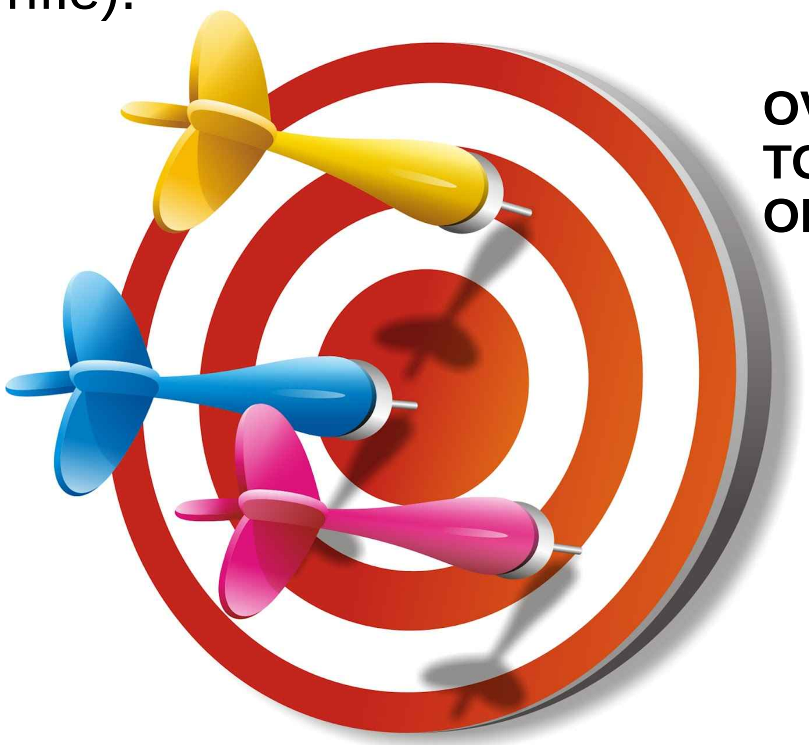
Hadron Therapy in the world

- Gaining increasing importance -> growing number of centers in the world.
- >70 centers in operation; > 40 under construction; ~20 planned.

Hadron therapy centers in the world
(from http://ptcog.web.psi.ch/ptcentres.html)

But...

- High precision is not an advantage if the aim is not correct (machine gun vs. precision rifle).

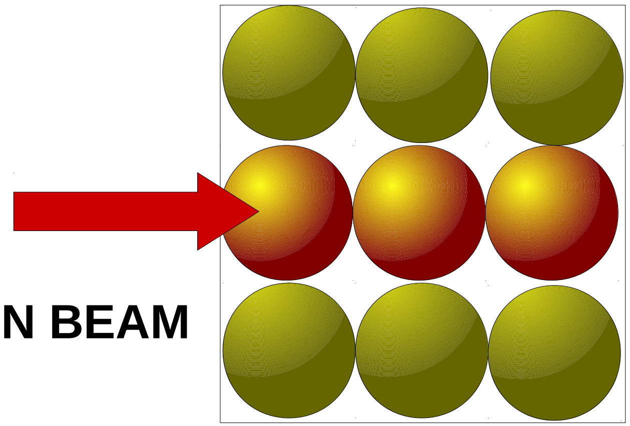


- Large margins have to be applied in treatment planning.

- Range uncertainties are considered one of the main obstacles for a wider application of this techniques

Real-time monitoring is essential

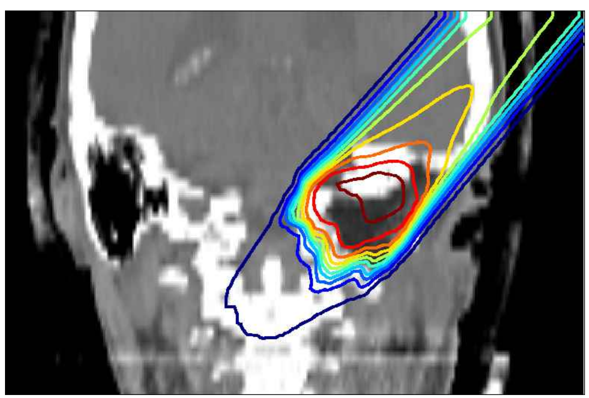
Treatment monitoring



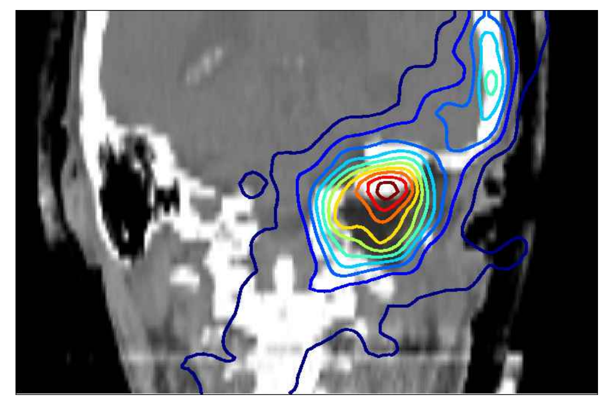
IRRADIATED TISSUE ATOMS

ION BEAM

DOSE DEPOSITION BY ELECTRONS THROUGH IONIZATION (electromagnetic interaction)

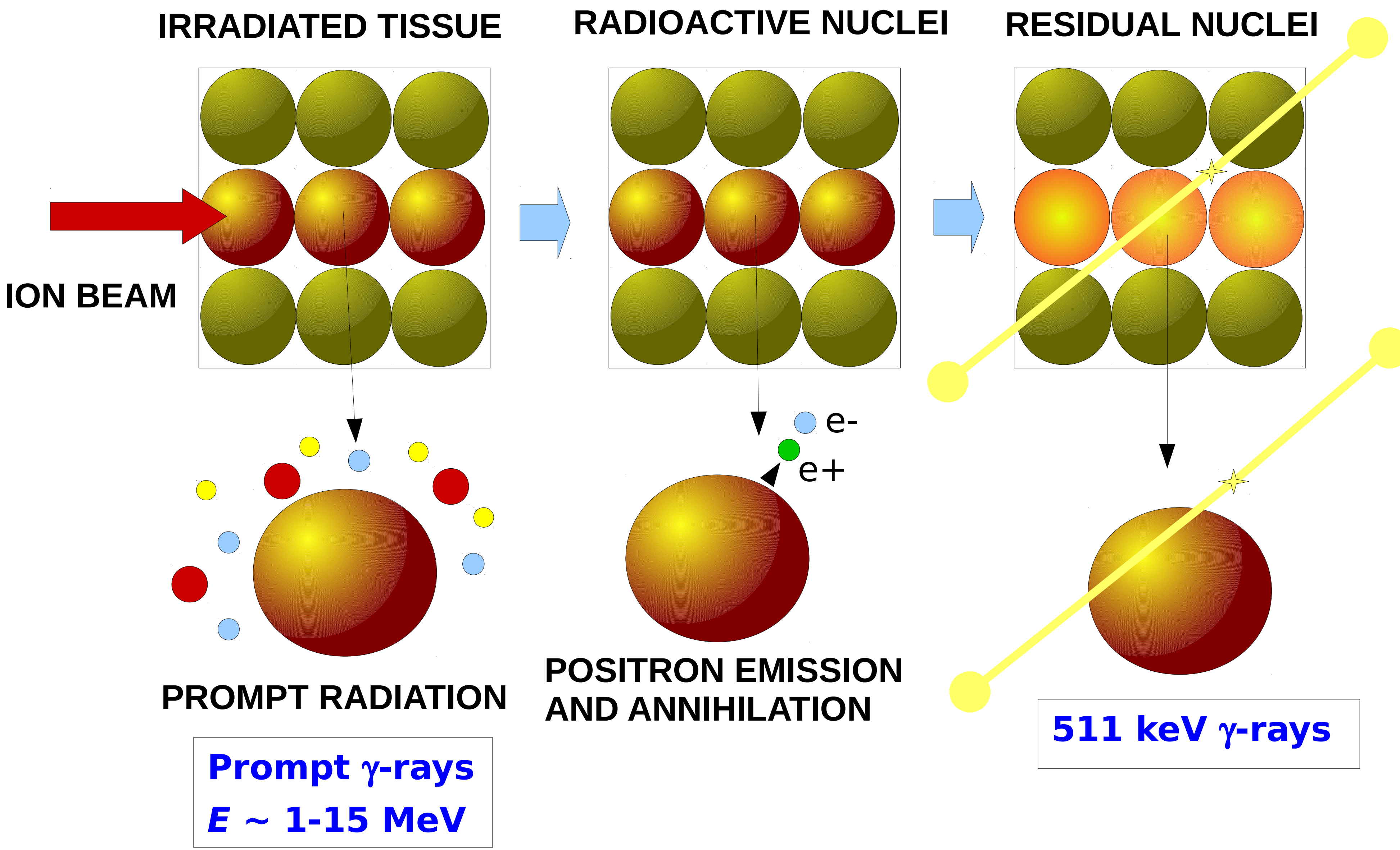


EMISSION OF SECONDARY PARTICLES (nuclear interaction)

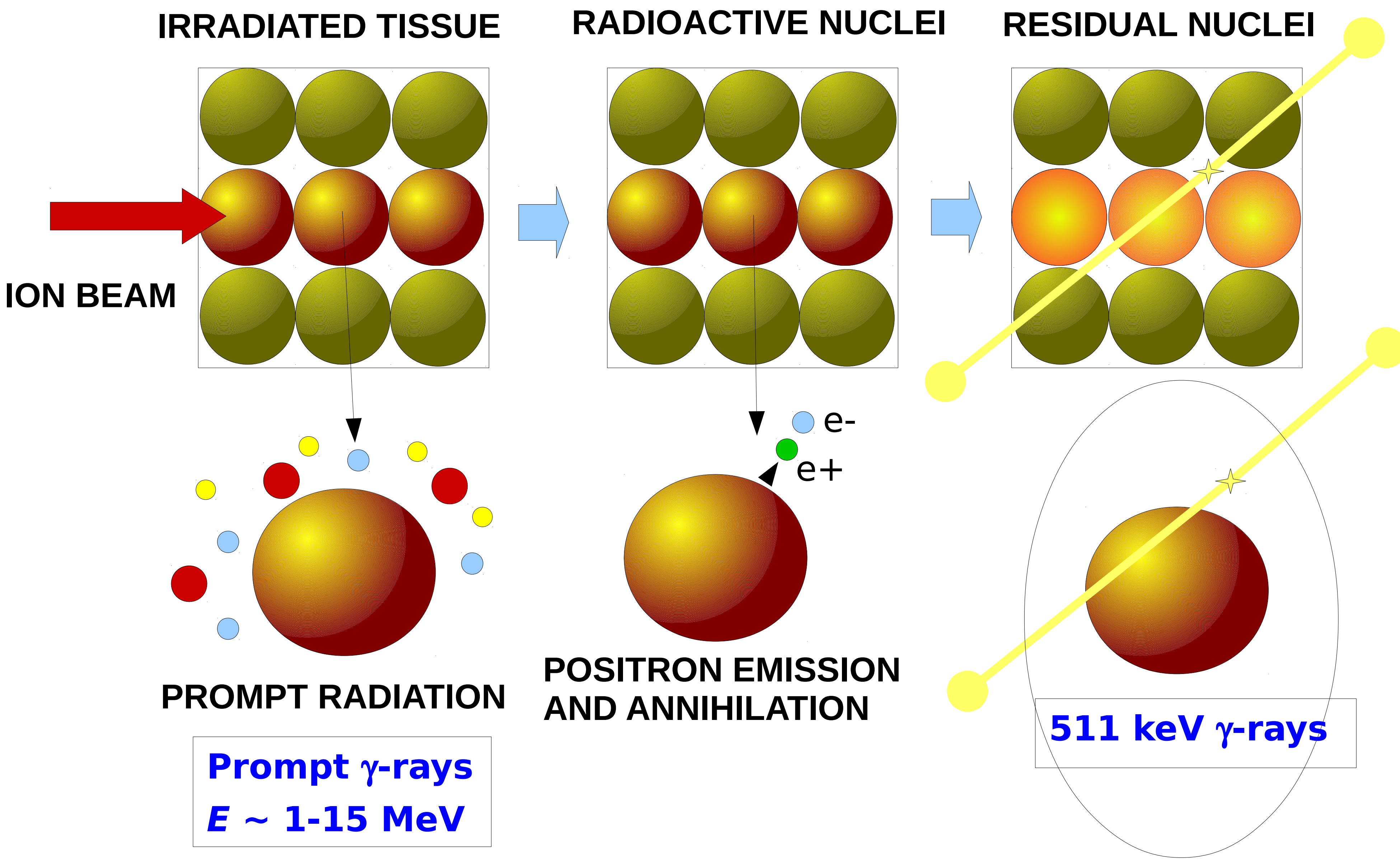


- Different mechanisms, but correlated
- Indirect estimation of dose deposition- can be used for monitoring

Treatment monitoring

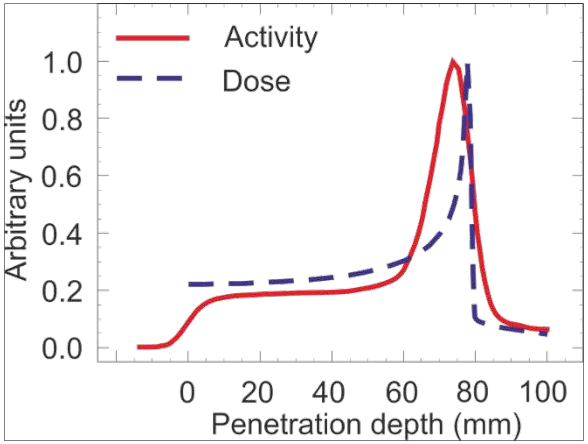


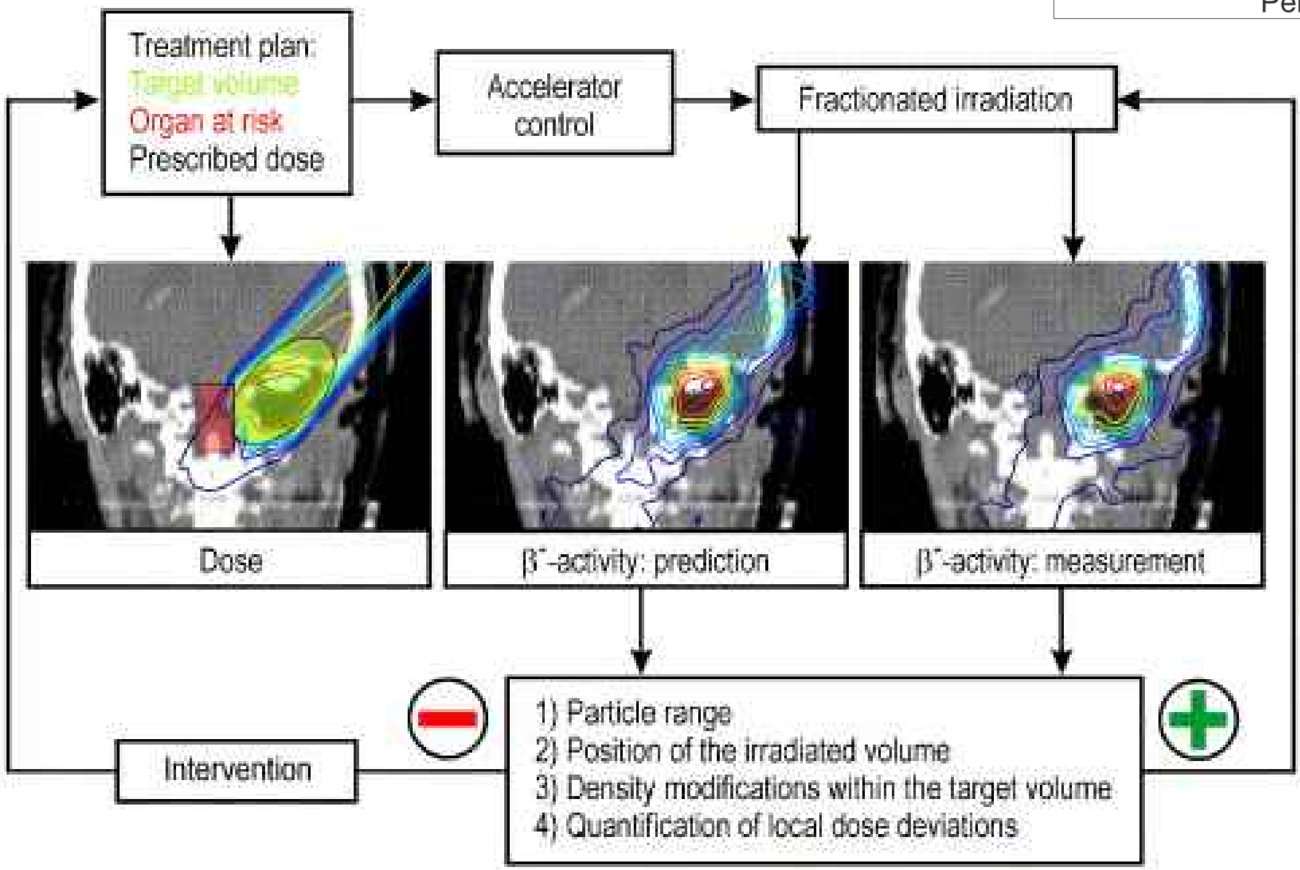
Treatment monitoring



Current monitoring - PET

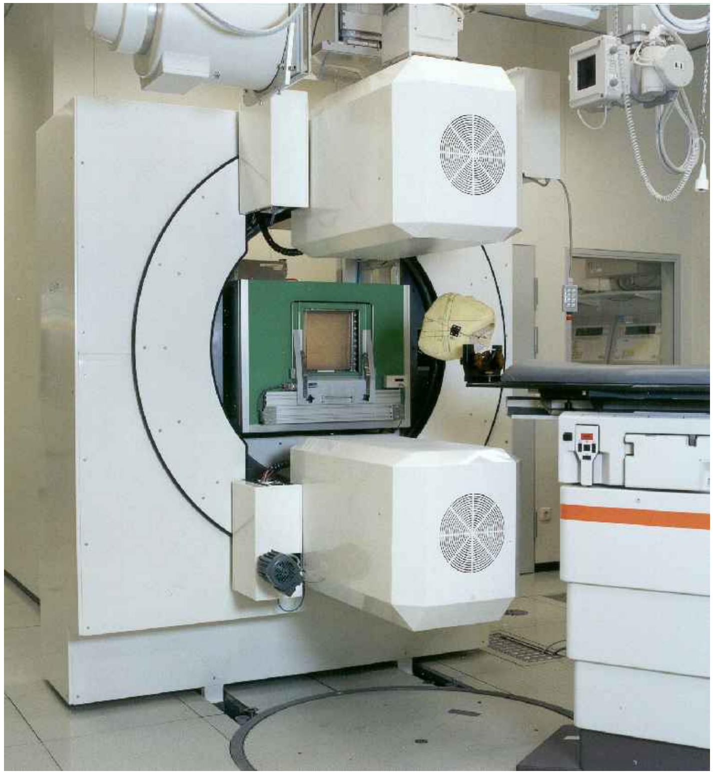
- Positron Emission Tomography (PET) + MC currently employed.
- Verification: comparison of β+ activity predicted from planned dose and measured with PET.





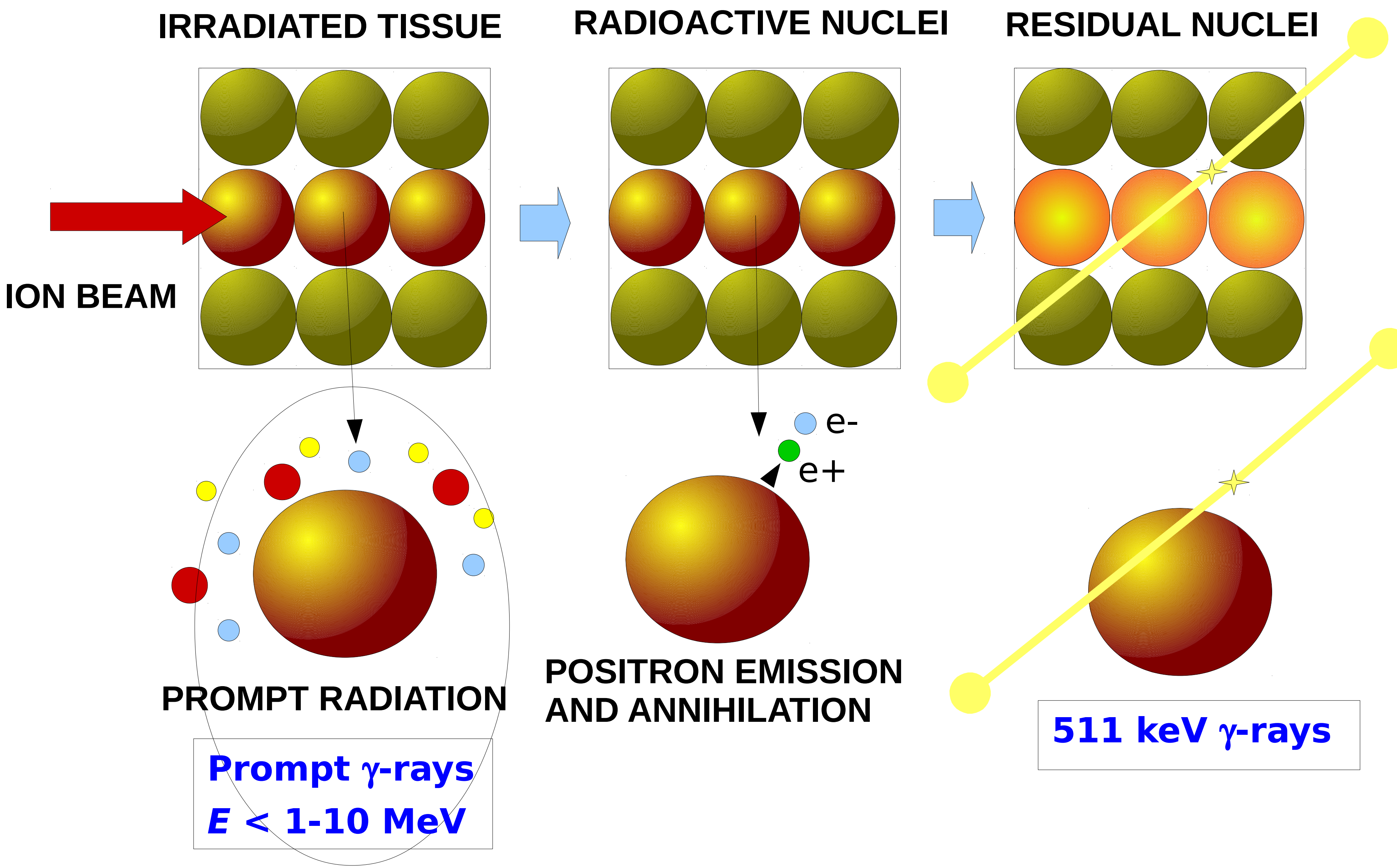
PET limitations

- PET Limitations:
  - Positron production does not follow irradiation immediately.
  - Biological washout- activity carried away by metabolic processes.
  - Low amount of $\beta+$ activity induced- low efficiency.
  - Difficult online studies – partial ring.
  - Photons produce significant background.



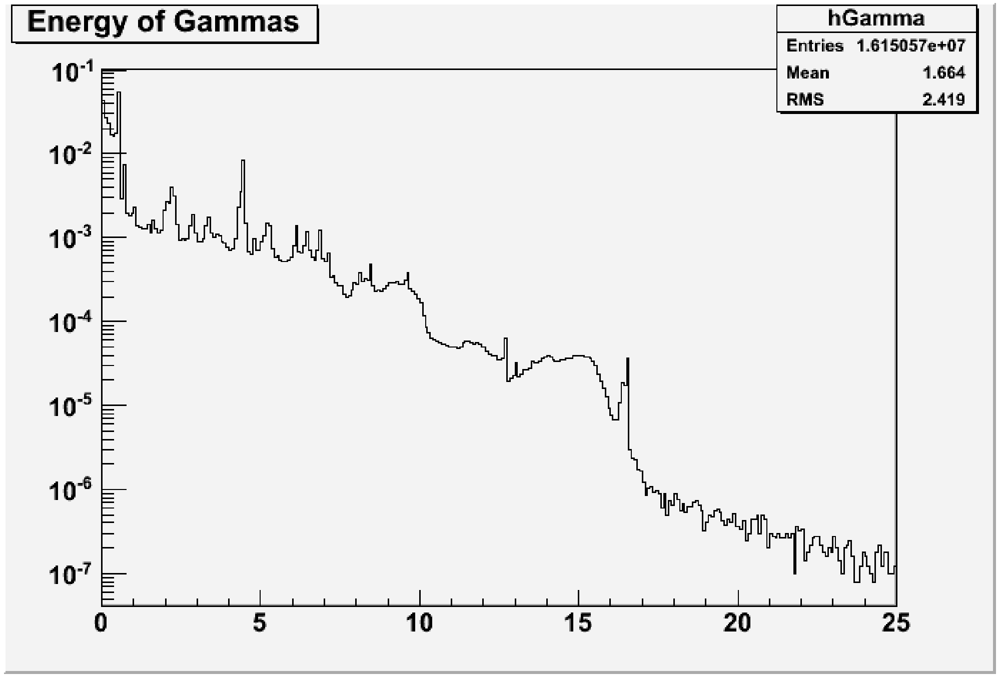
- PET improvements:
  - Improved systems.
  - Models for washout.
  - Use of short-lived isotopes.
  - TOF PET to minimize gap effects.

Treatment monitoring



Prompt gammas

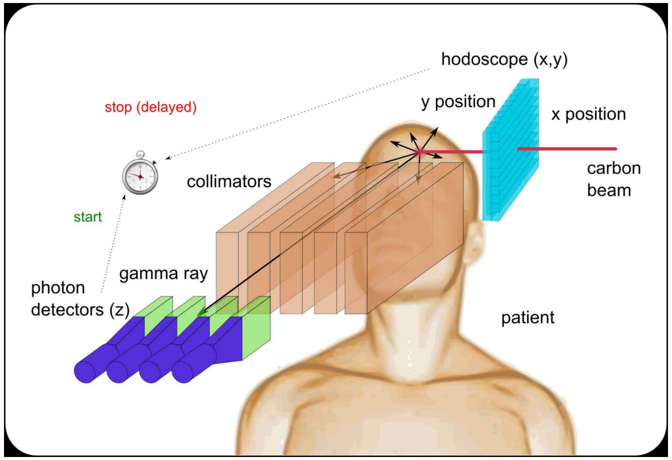
- Prompt gammas also emitted from nuclei excited during therapy and correlated with dose.
  - MeV in a continuous energy spectrum. High energies.
  - Emitted within ns after irradiation.
  - Higher amount than positron emitters.

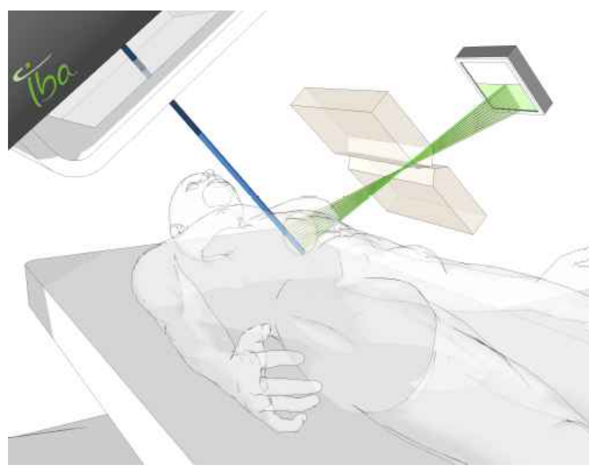


Energy (MeV)

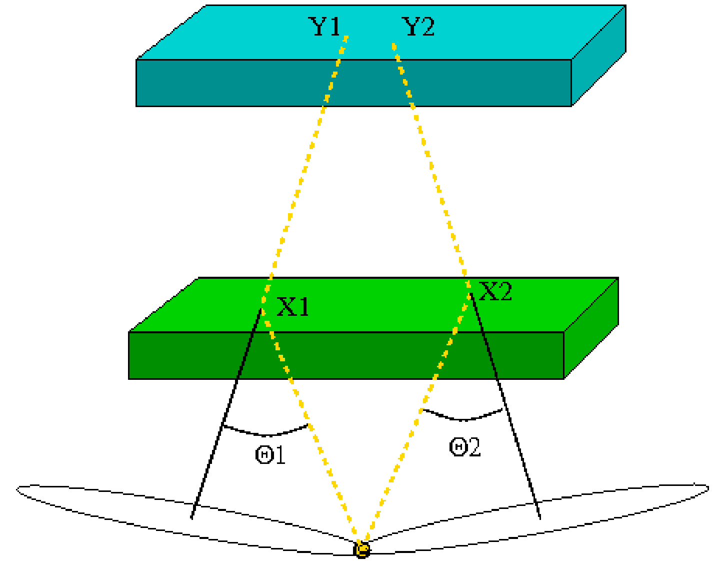
How to detect them?

COLLIMATED





COMPTON



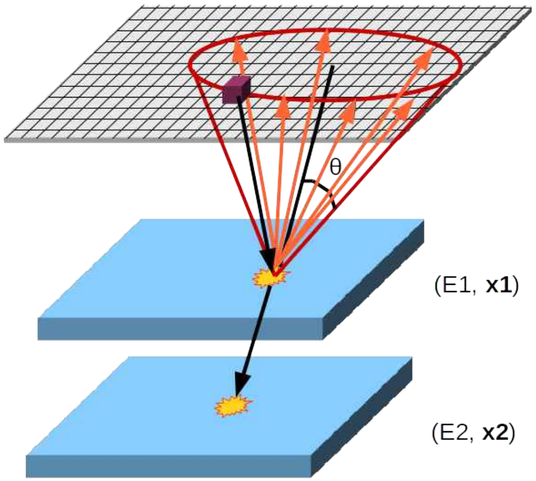
$$\cos\varphi = 1 - m_0 c^2 \left(\frac{1}{E_{\gamma'}} - \frac{1}{E_\gamma} \right)$$

$$E_\gamma = E_{e^-} + E_{\gamma'}$$

F. Roellinghoff et al.
Phys. Med. Biol. 59 (2014)

J. Smeets.
Phys. Med. Biol. 57 (2012)

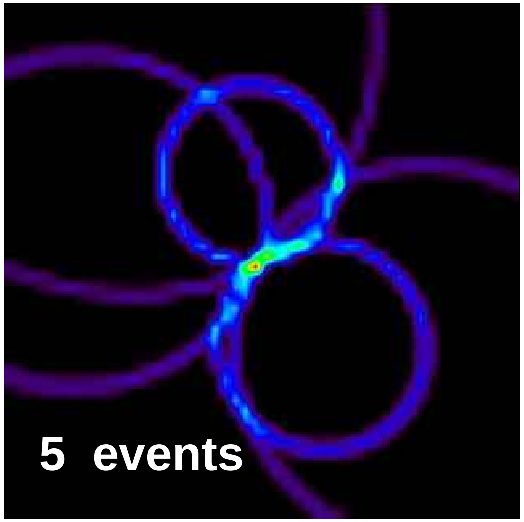
Compton Imaging

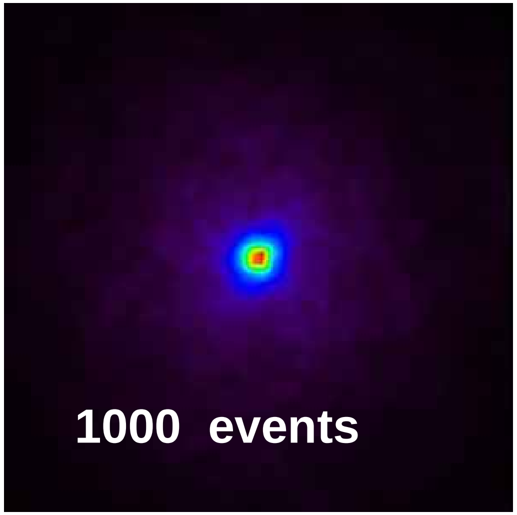


The cone surface is projected to the reconstruction volume.

The intersection of several cone surfaces yields the position of the source.

Backprojection

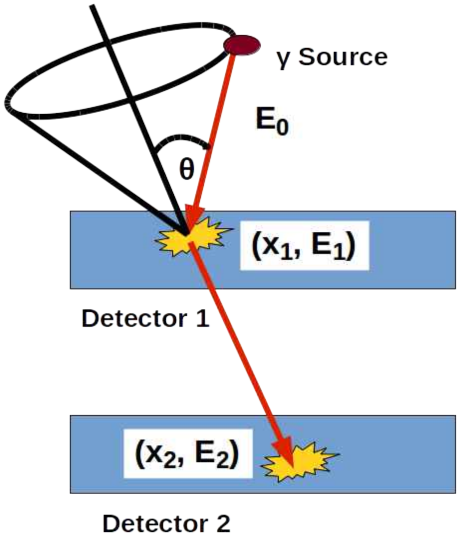




+ List mode ML-EM

$$\lambda_j^{n+1} = \frac{\lambda_j^n}{s_j} \sum_{i=0}^{N} \frac{t_{ij}}{\sum_k t_{ik} \lambda_k^n}$$

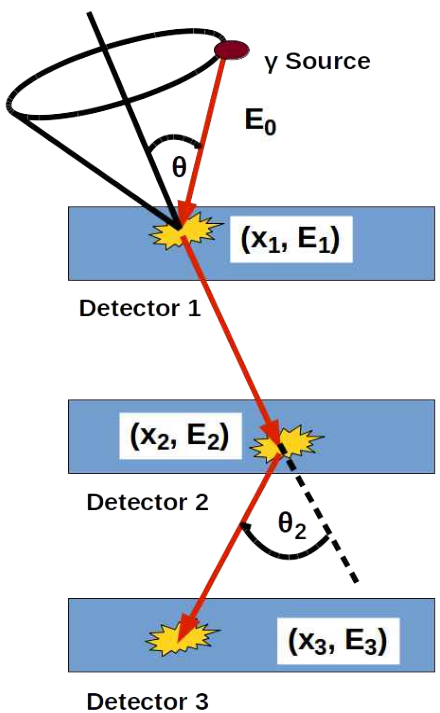
Compton camera configuration



Scatterer + absorber: 2 interactions

Problems if the photon energy is unknown or if it can escape (MeV)

$$cos\theta = 1 - m_0c^2\left(\frac{1}{E_0 - E_e} - \frac{1}{E_0}\right)$$



Multilayer: 3 interactions in 3 detectors (+ correct ordering):

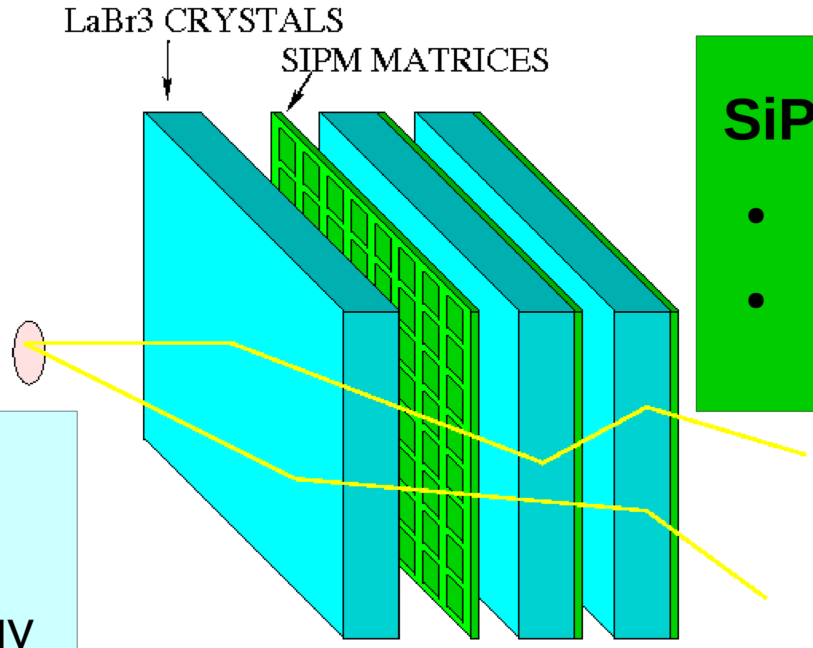
- Energy determined
- lower efficiency

$$\cos(\theta) = 1 - \frac{E_1 m_e c^2}{E_0(E_0 - E_1)}$$

$$E_0 = E_1 + \frac{1}{2}\left(E_2 + \sqrt{E_2^2 + 4\frac{E_2 m_e c^2}{1 - \cos\theta_2}}\right)$$

Compton telescope @ IRIS

Three detector layers



SiPM arrays:
- Compact
- fast

LaBr$_3$ CRYSTALS:
- high Compton probability,
- high light yield=> good energy and timing resolution

Easy to operate.

- Combination of :
  - 2 int events (high efficiency) +
  - 3 int events (high resolution).

+ Estimate both position and energy simultaneously from 2-interaction events

NO ABSORPTION REQUIRED

Compton telescope @ IRIS

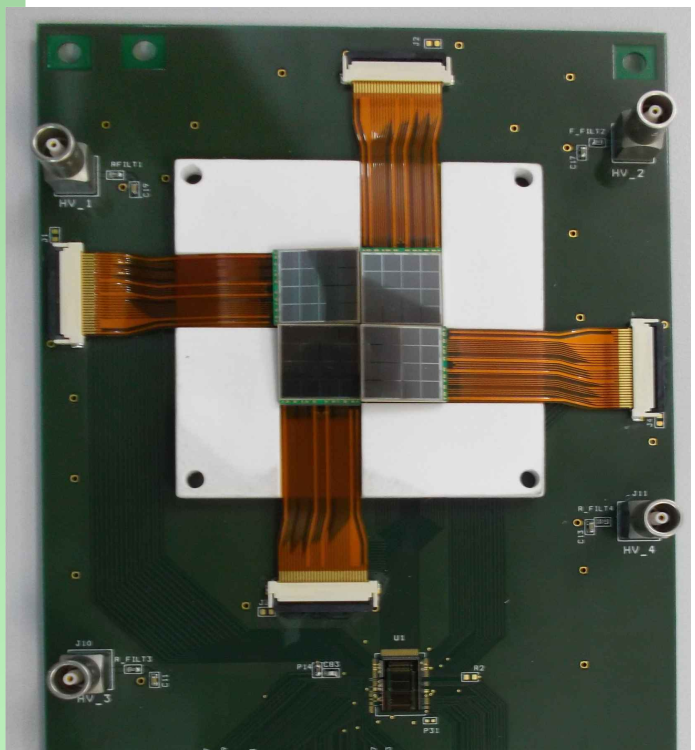
Detectors 2 and 3

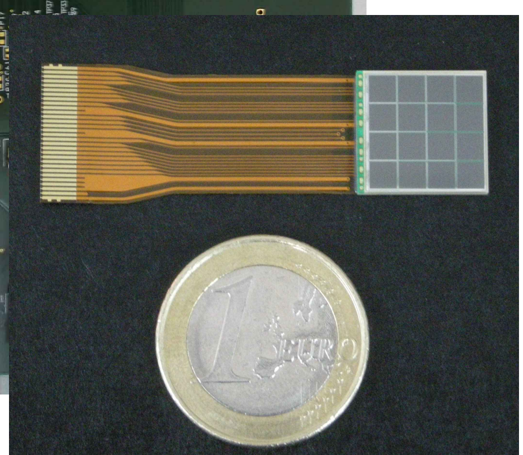
Detector 1

Detectors

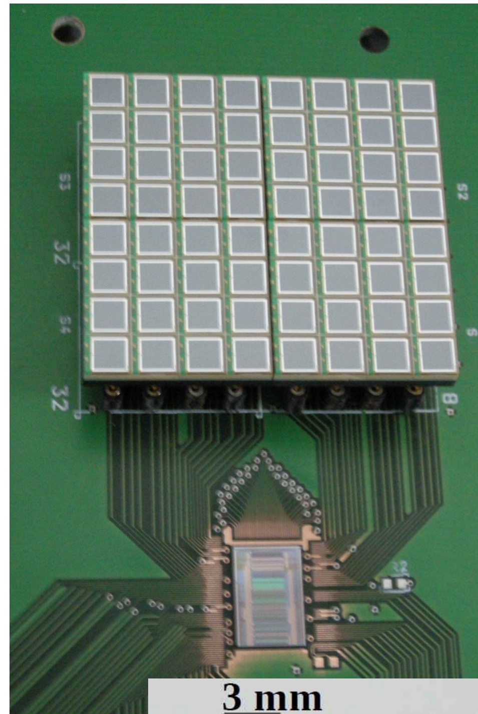
Monolithic crystals:
E resol: 7-10% FWHM
Sp resol: 1.3 mm FWHM
Expected DOI:~ 2 mm FWHM,
~ 6 mm FWTM

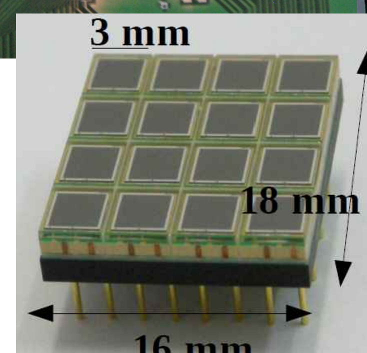
Detector 1

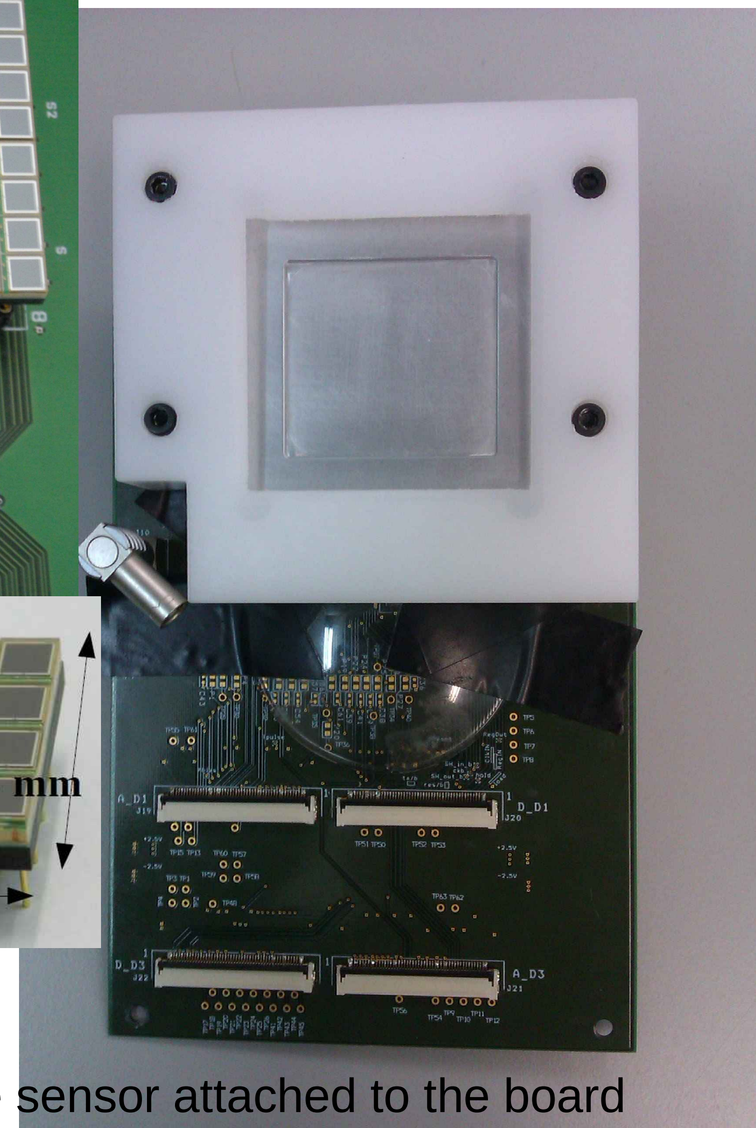




Detectors 2 and 3



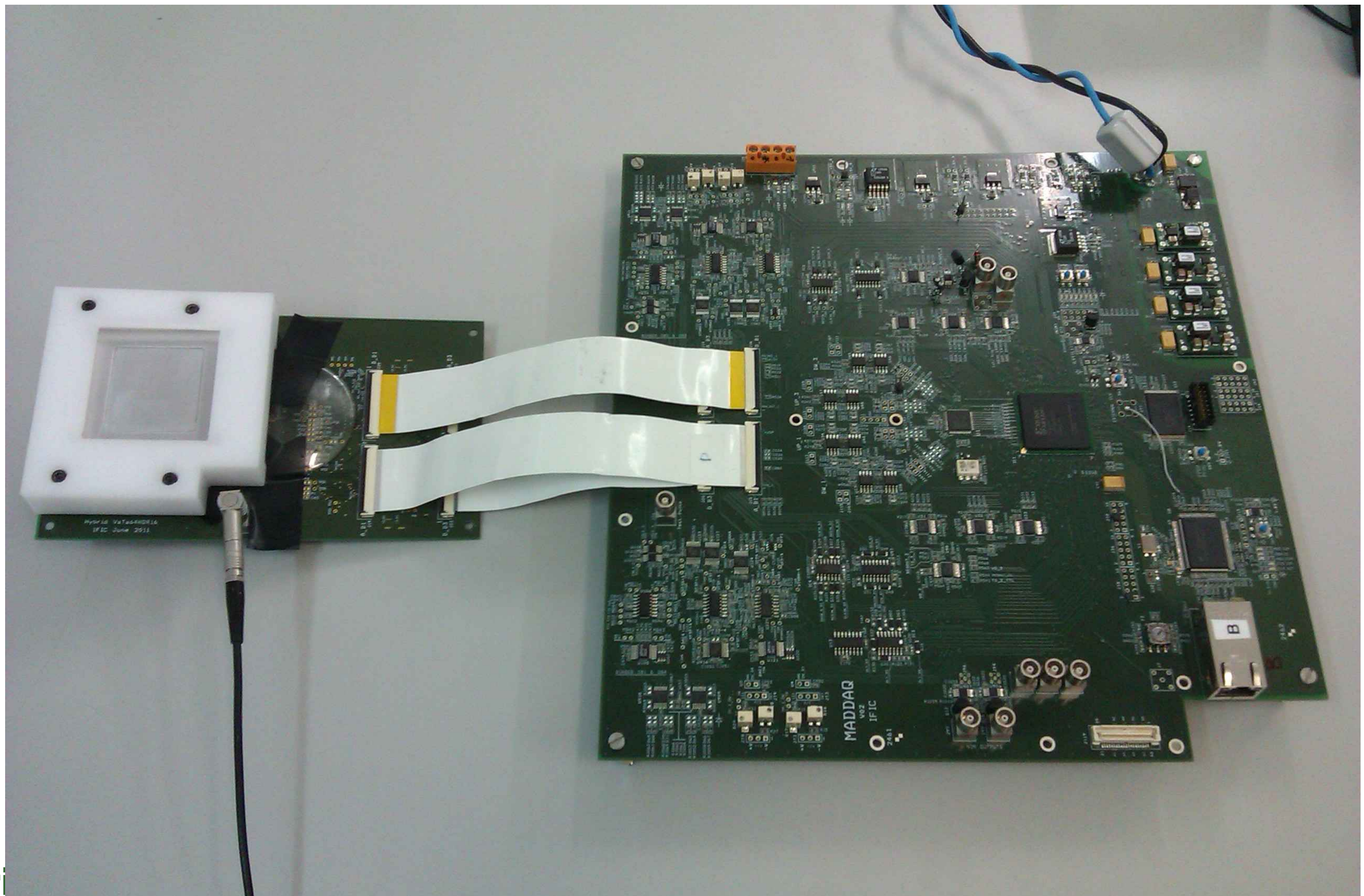




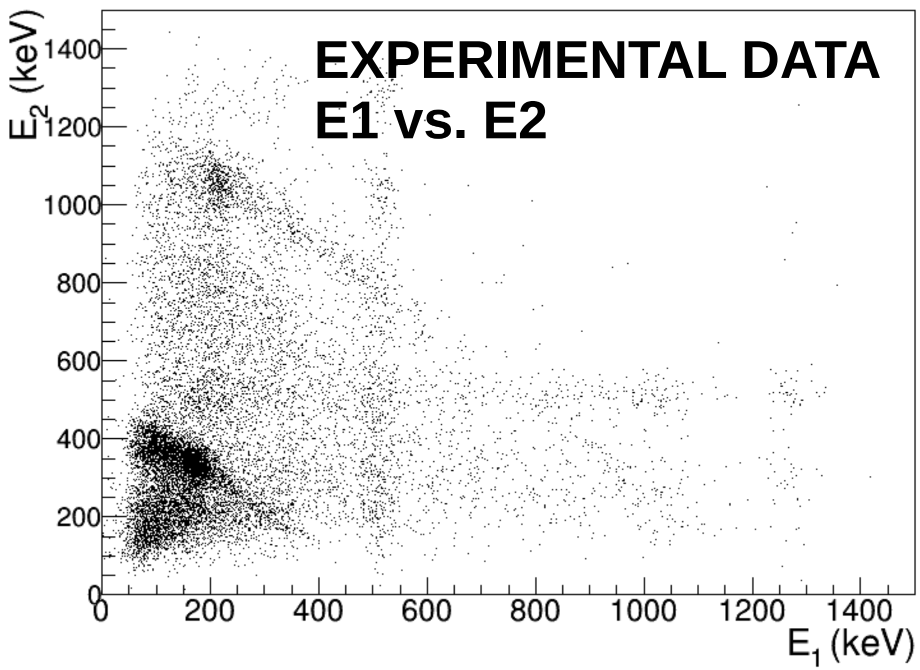
Temperature sensor attached to the board

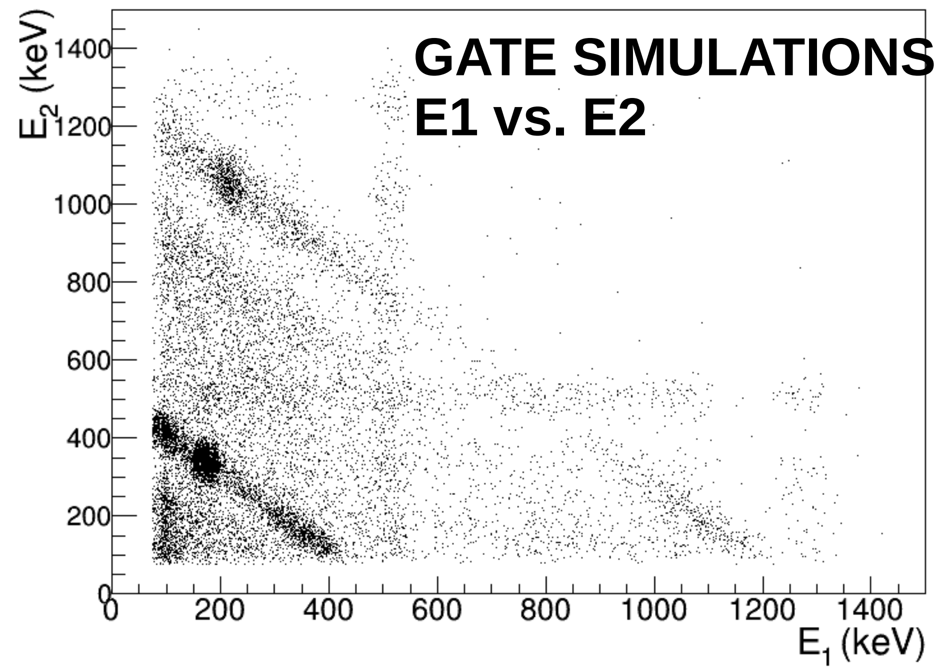
DAQ system

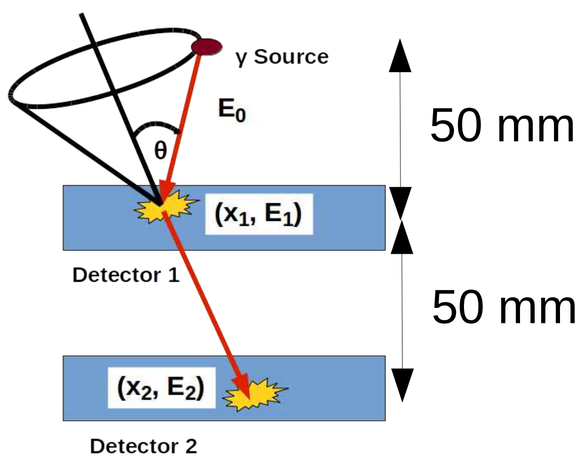
- VATA64HDR16 ASIC from IDEAS – 64 channels
- Connected to a DAQ system made at IFIC.
- Compact and portable system

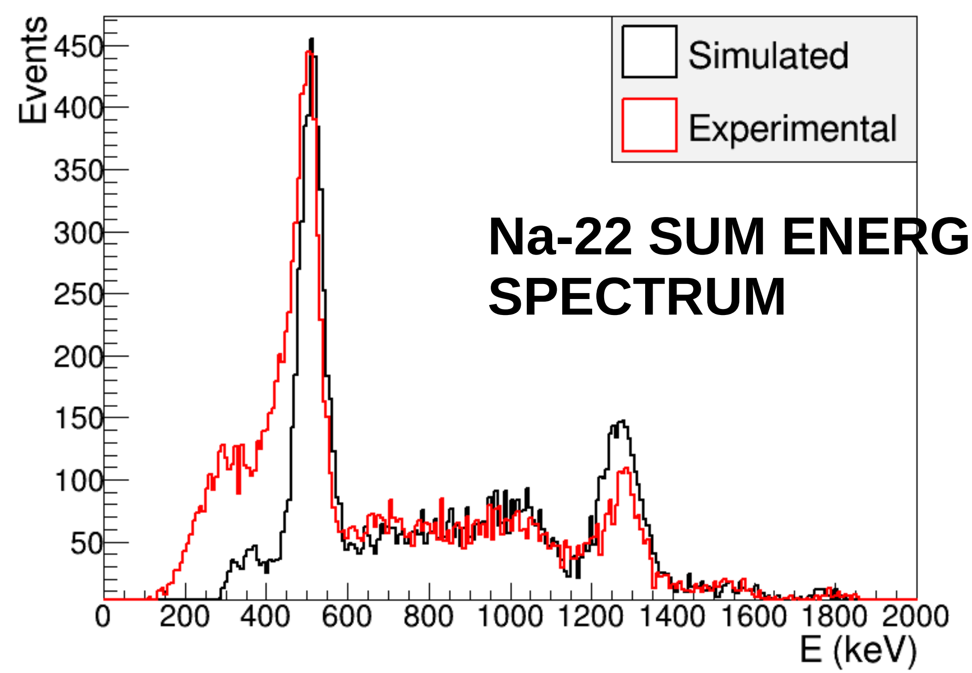


Two-layer simulations vs. data



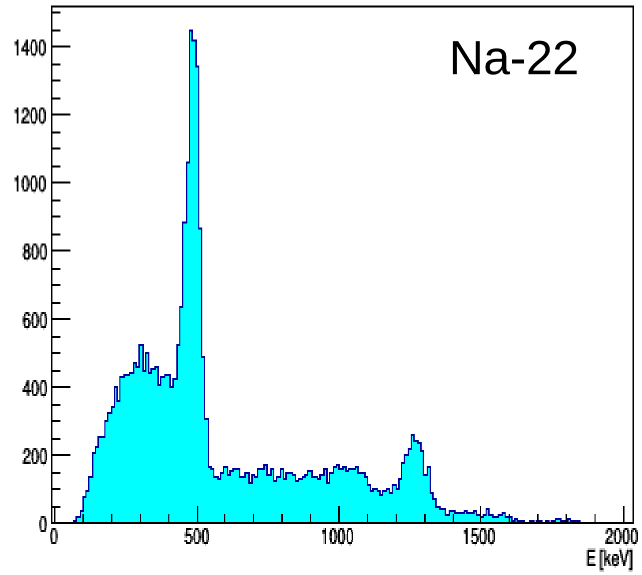


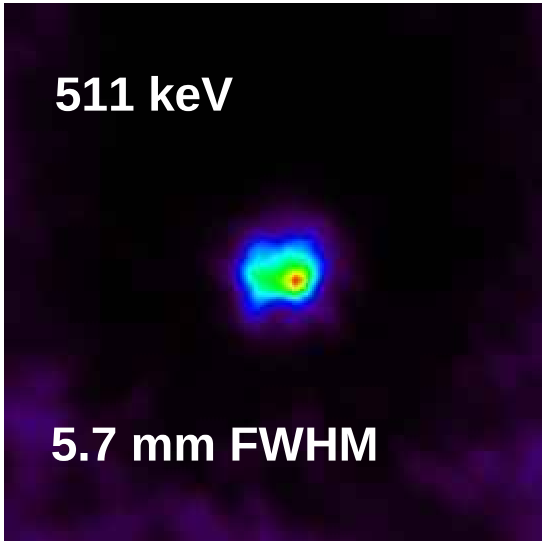


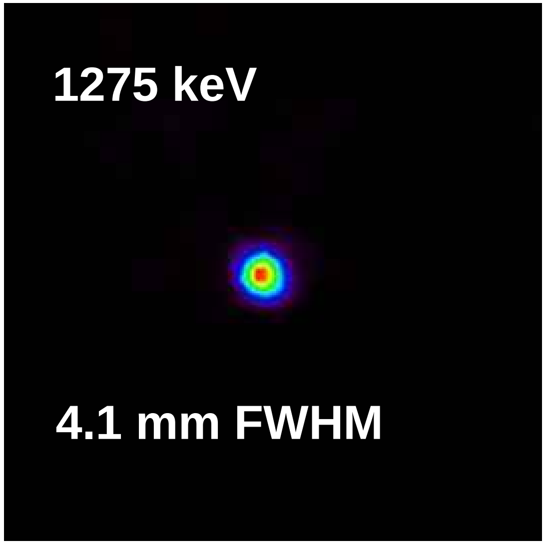


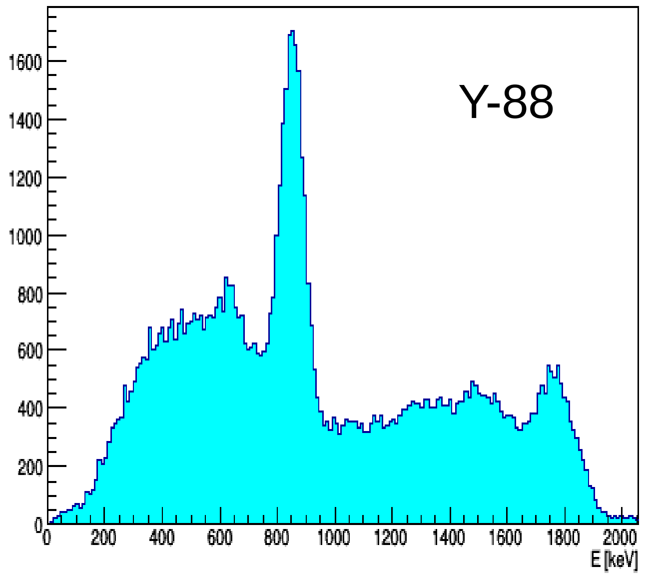
Two planes: different energies

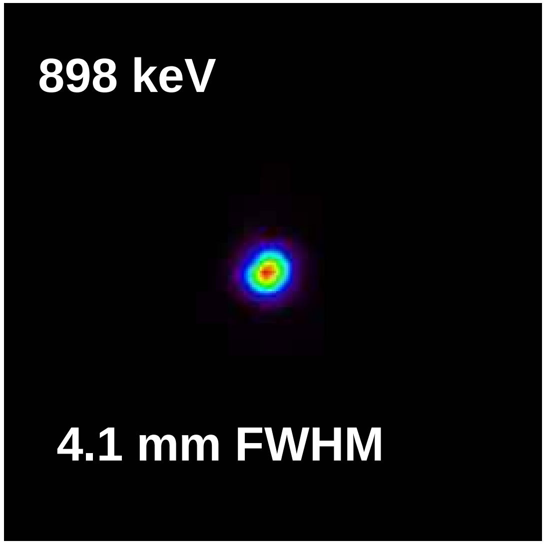
Sum Spectrum

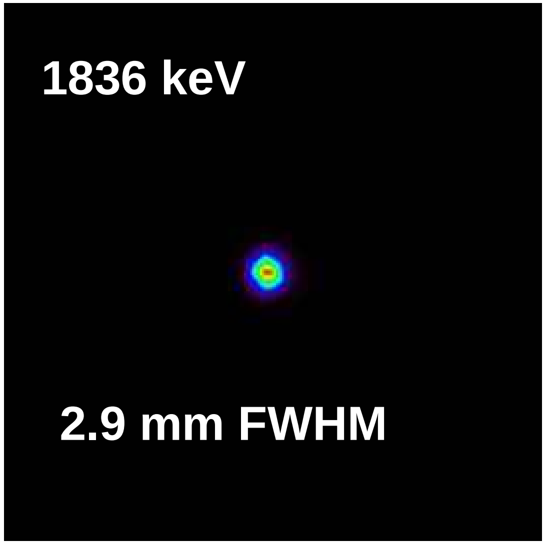








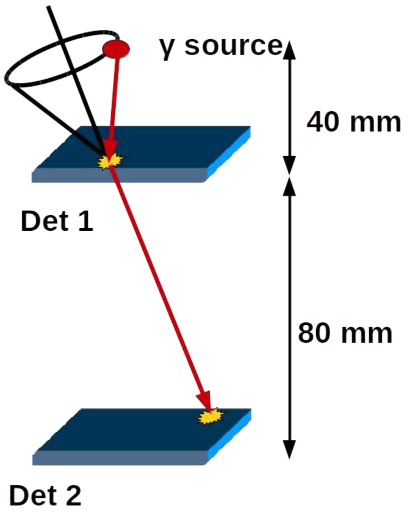




RESOLUTION IMPROVEMENT WITH ENERGY

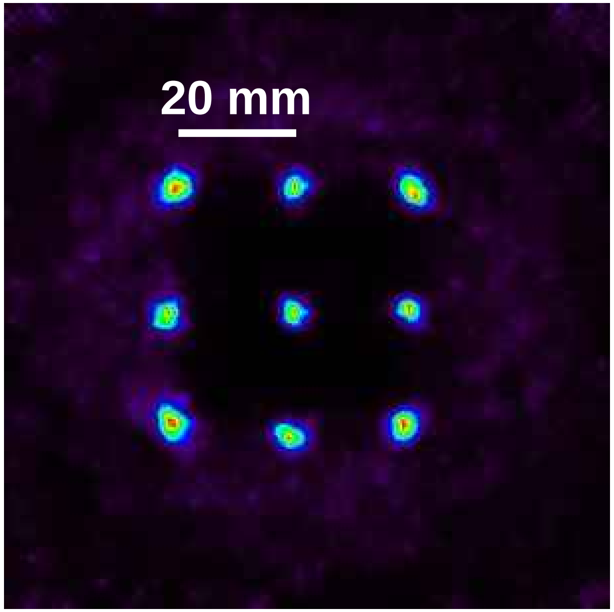
Two planes: different positions

- Sources placed in different positions, separated 20 mm.
- Points reconstructed separately.

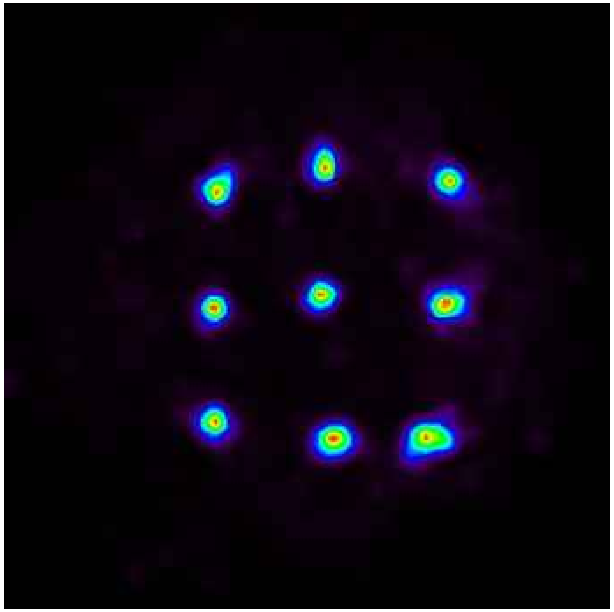


GOOD POSITIONING ACCURACY

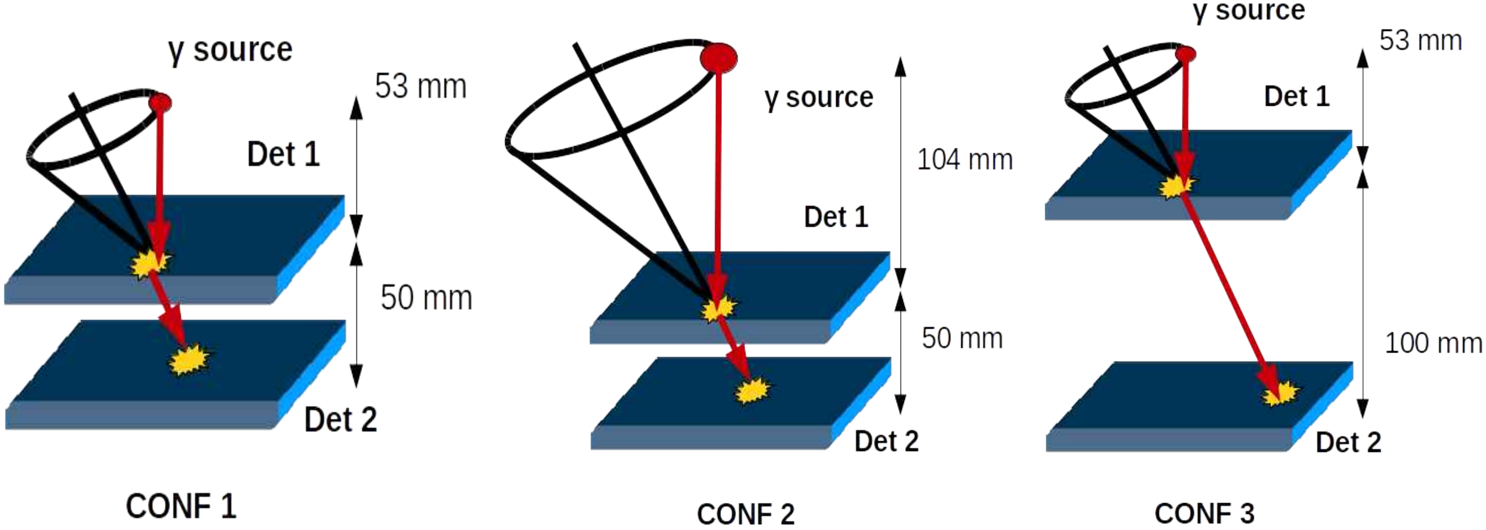
Na-22 selecting **1275 keV** peak



Y-88 selecting **1836 keV** peak

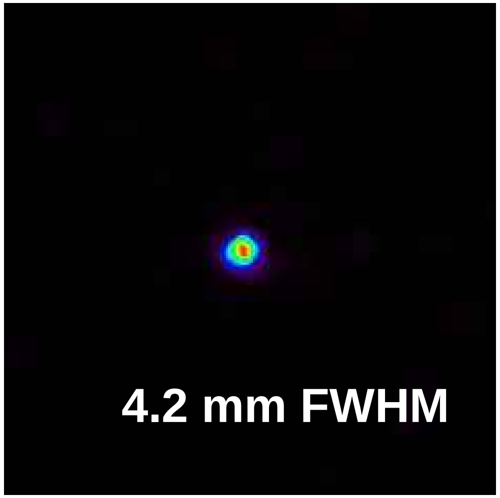


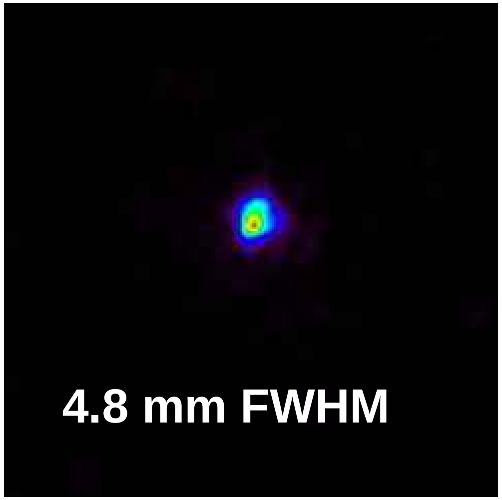
Two planes: different configurations

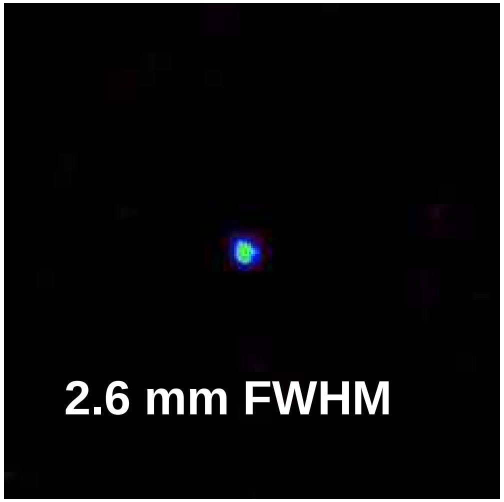


GEOMETRY DETERMINES RESOLUTION

TRADE-OFF WITH EFFICIENCY

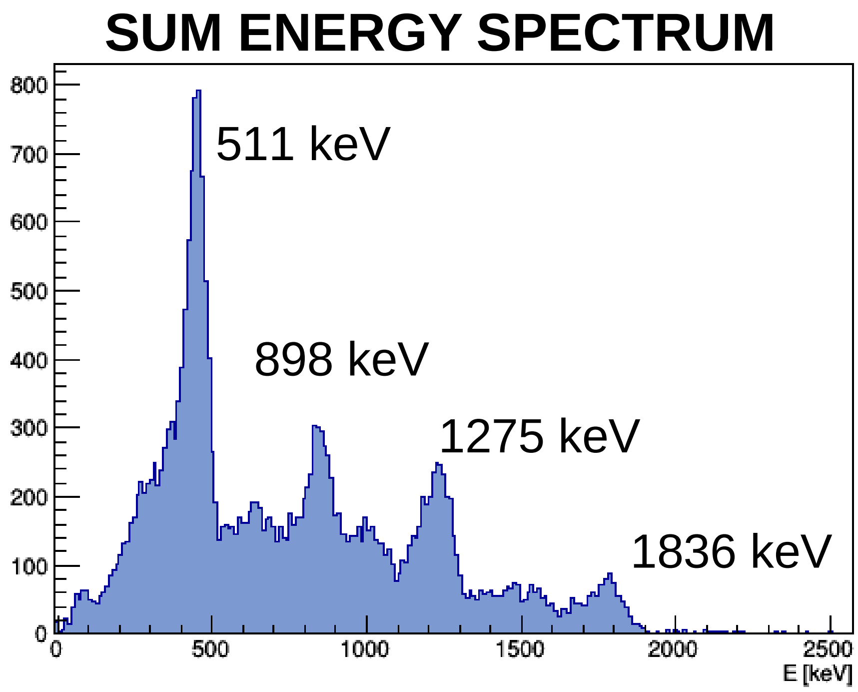


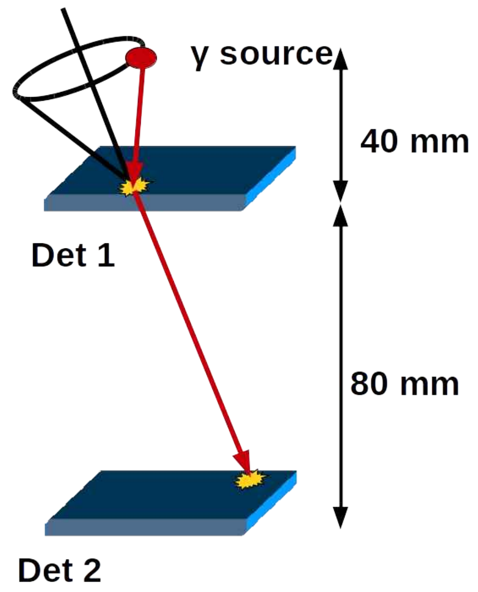


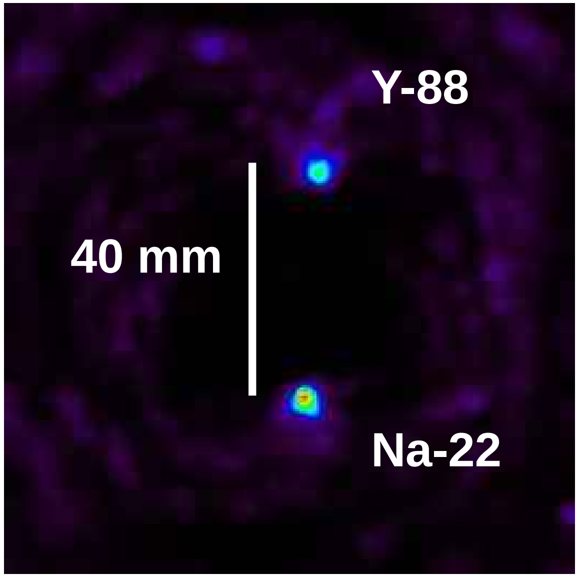


Na-22 selecting **1275 keV** peak

Two planes: Na-22 + Y-88



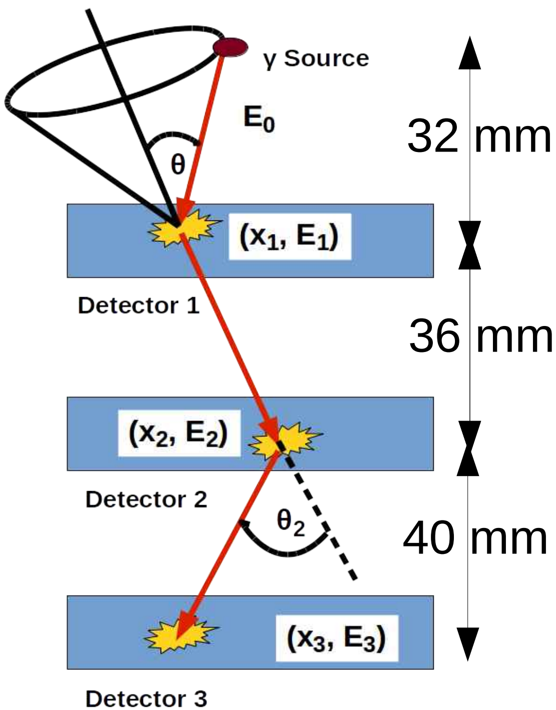


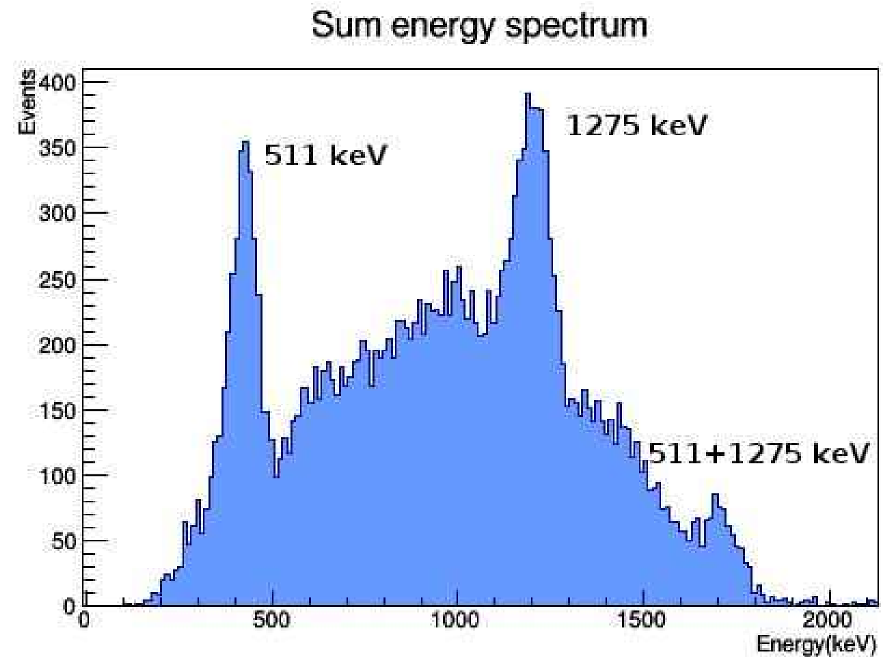


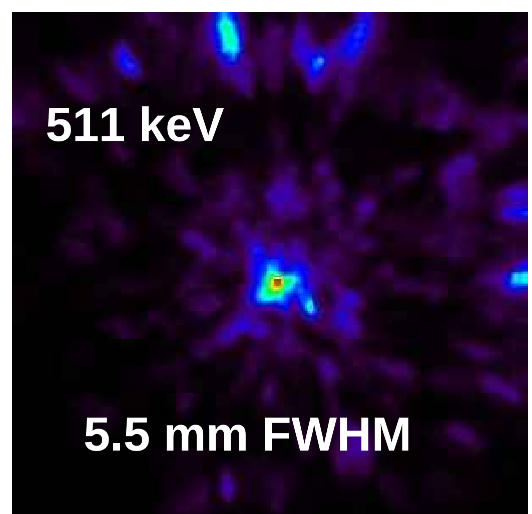
- Selecting 1275 and 1836 keV peaks
- Sources separated 40 mm.
- Data from both sources reconstructed together

Three planes: Na-22

Na-22: 650 keV< Esum < 1350 keV.

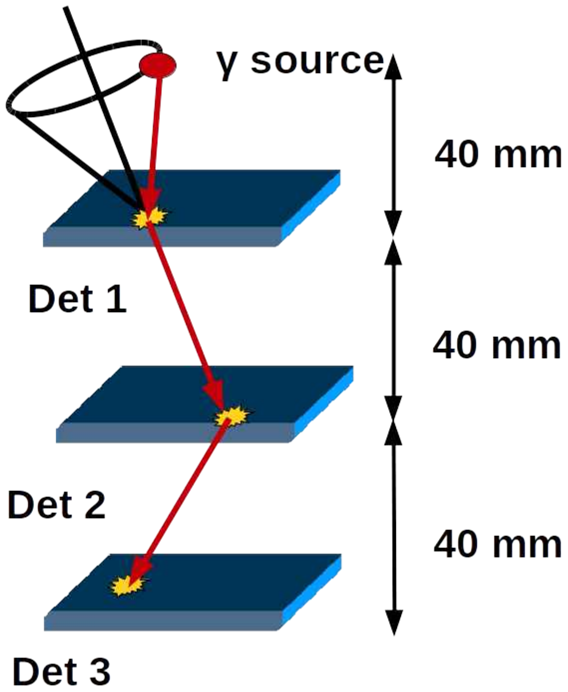


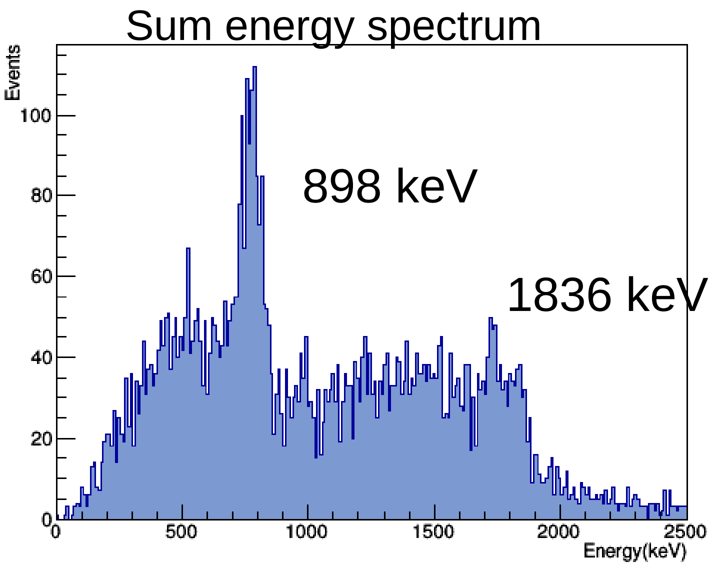


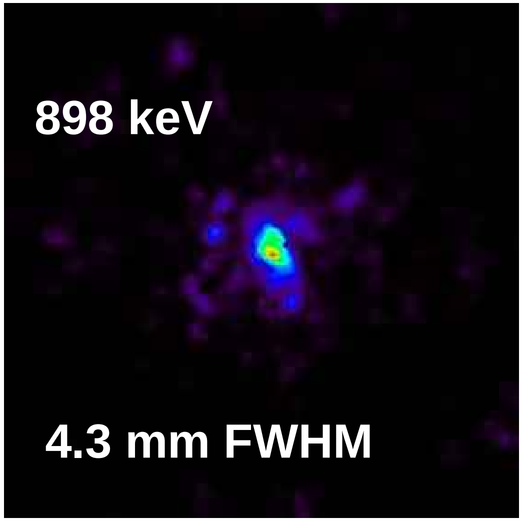


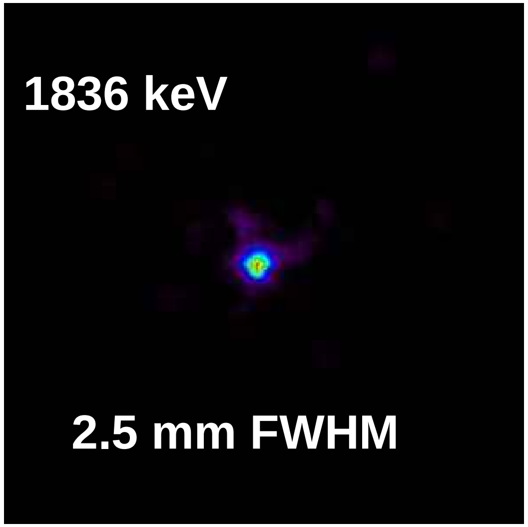
Three planes: Y-88

Y-88: 1100 keV< Esum < 1950 keV.

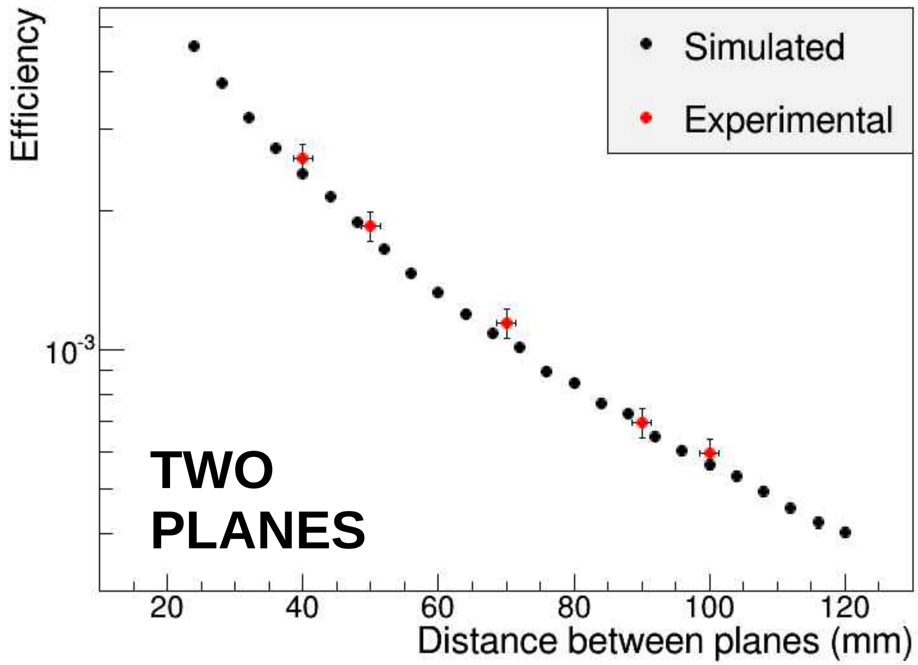


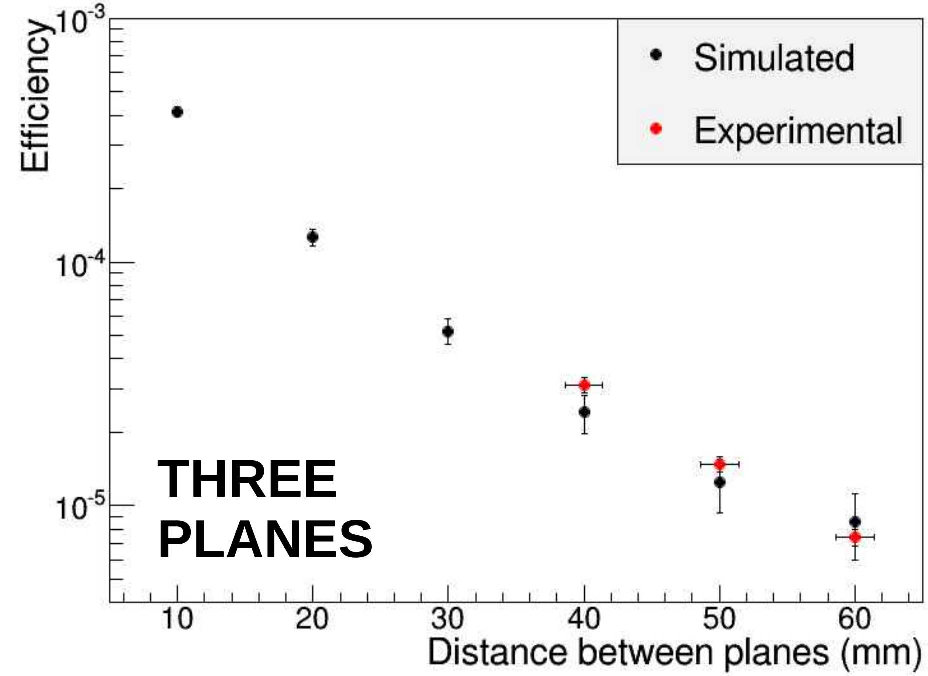


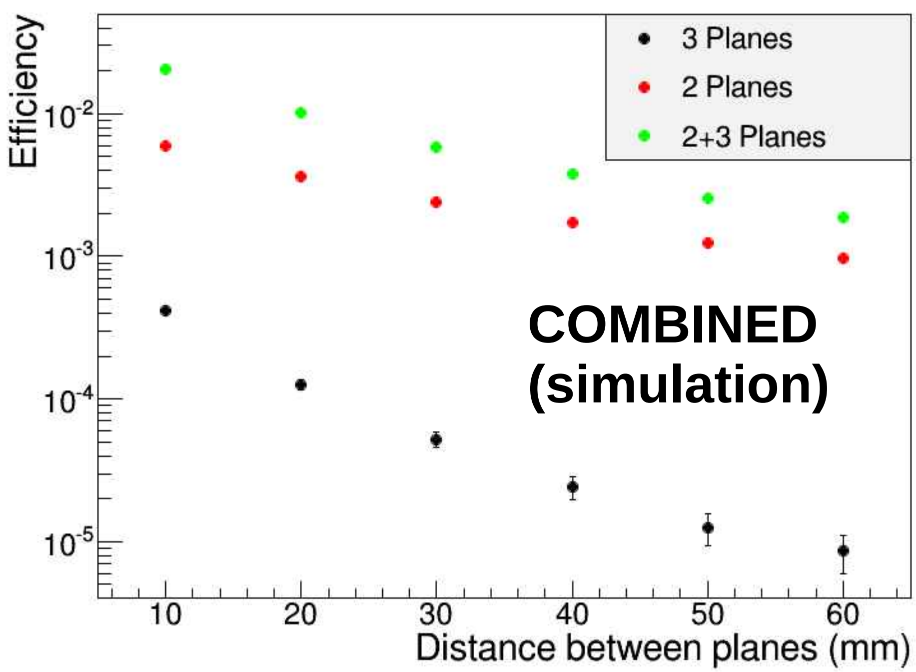




Efficiency



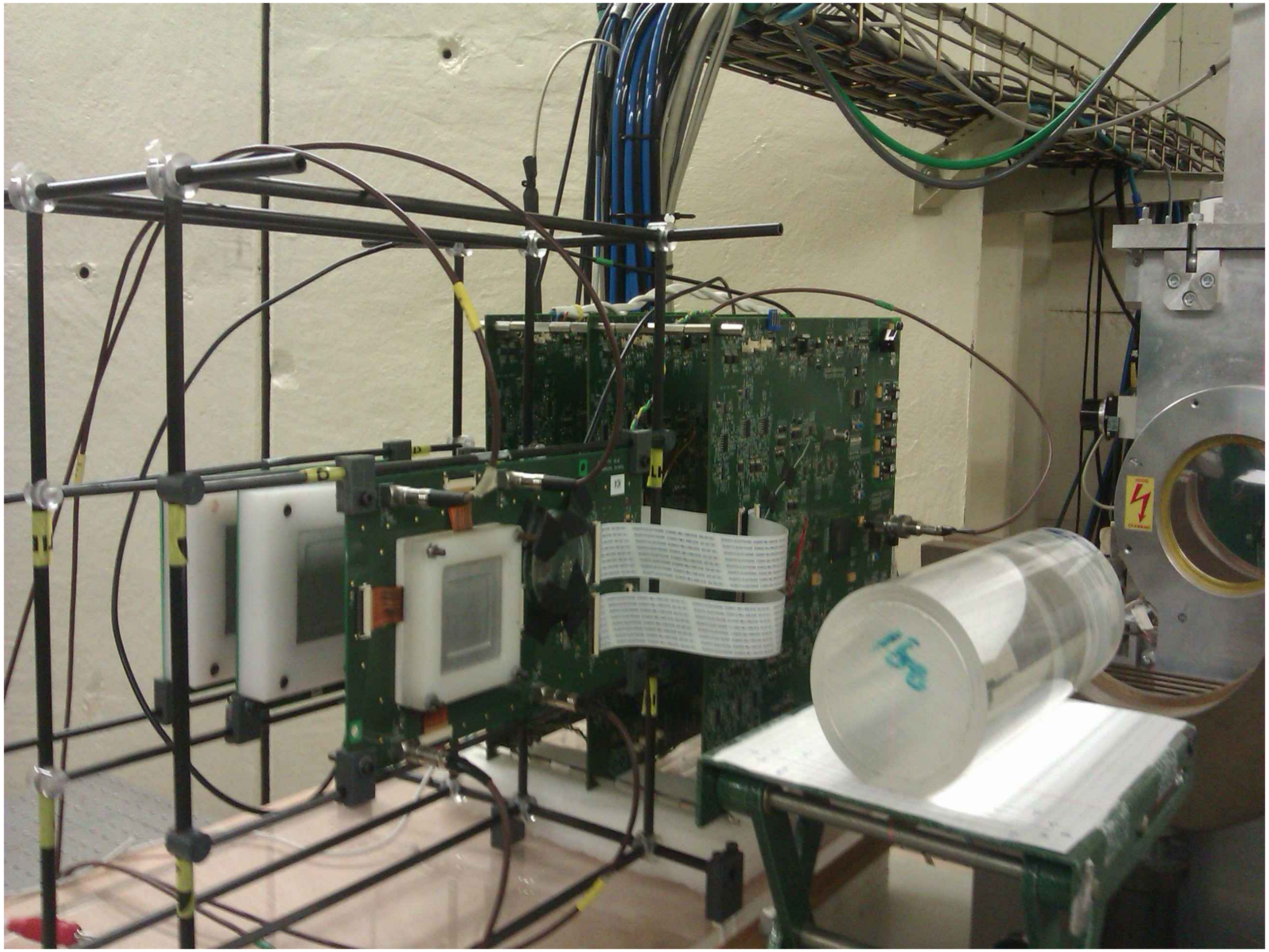




Final results submitted to PMB. E. Muñoz et al.

Tests in a proton beam

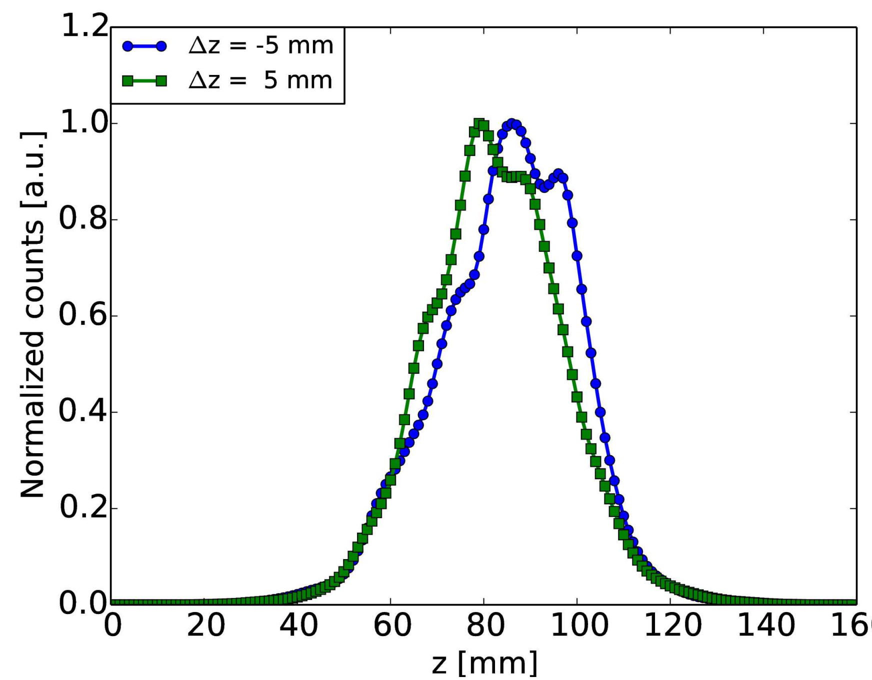
- Tests at KVI-CART, AGOR cyclotron (Groningen).
- Proton beam, 150 MeV, ~ 10^8 prot/sec.
- Graphite and PMMA targets.



Tests in a proton beam

- Data with two layers in coincidence.
- PMMA target shifted to simulate Bragg peak variations.

SHIFT OBSERVED IN BRAGG PEAK POSITION



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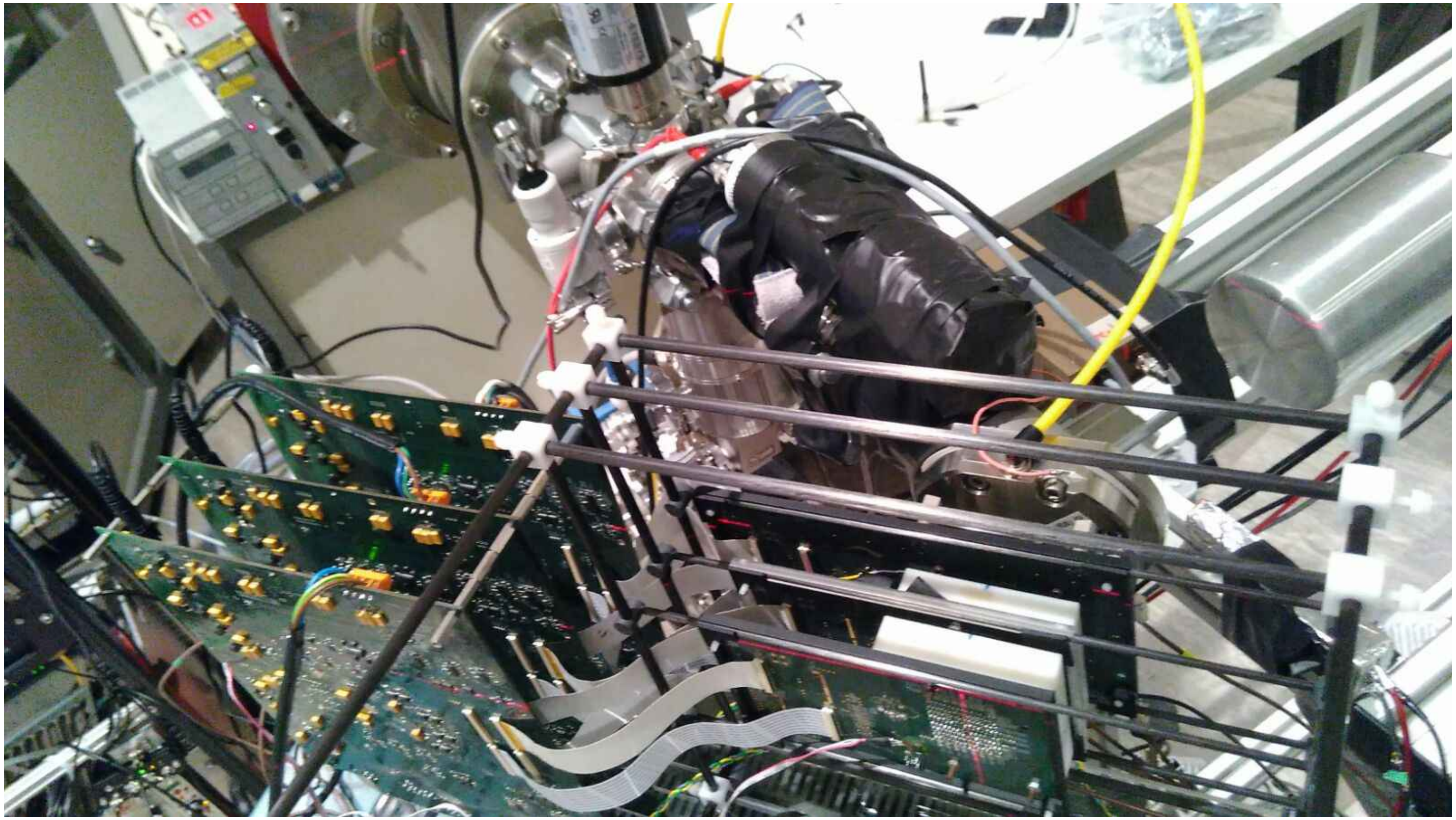
Tests with high energy gammas

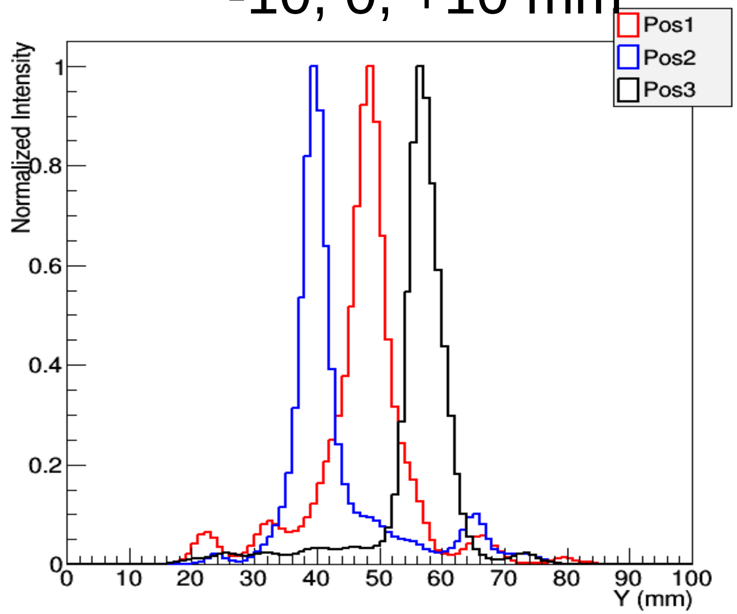
- Tests at HZDR 3MV Tandetron (Dresden).
- Gammas 4.439 MeV. $^{15}N(p,\alpha\gamma)^{12}C$ reaction.
- Low gamma emission rate.

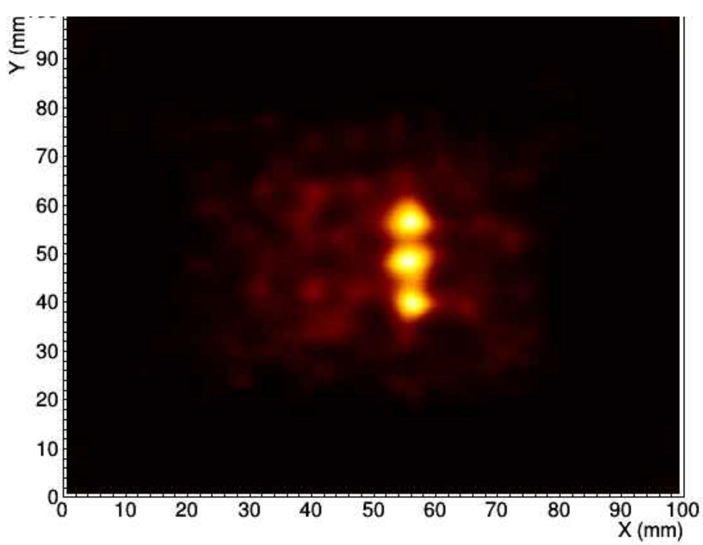


Tests with high energy gammas

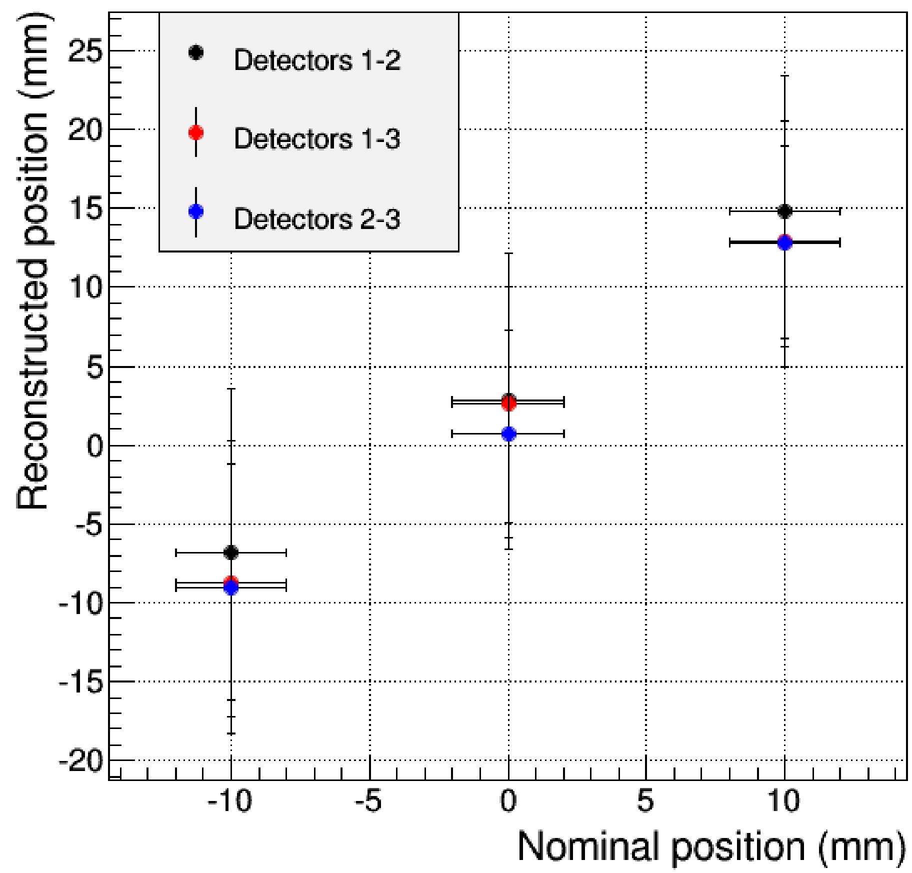
Results with layers 1-3 in coincidence:
source 43 mm, distance 55 mm.

-10, 0, +10 mm





Results with the three combinations of two detectors



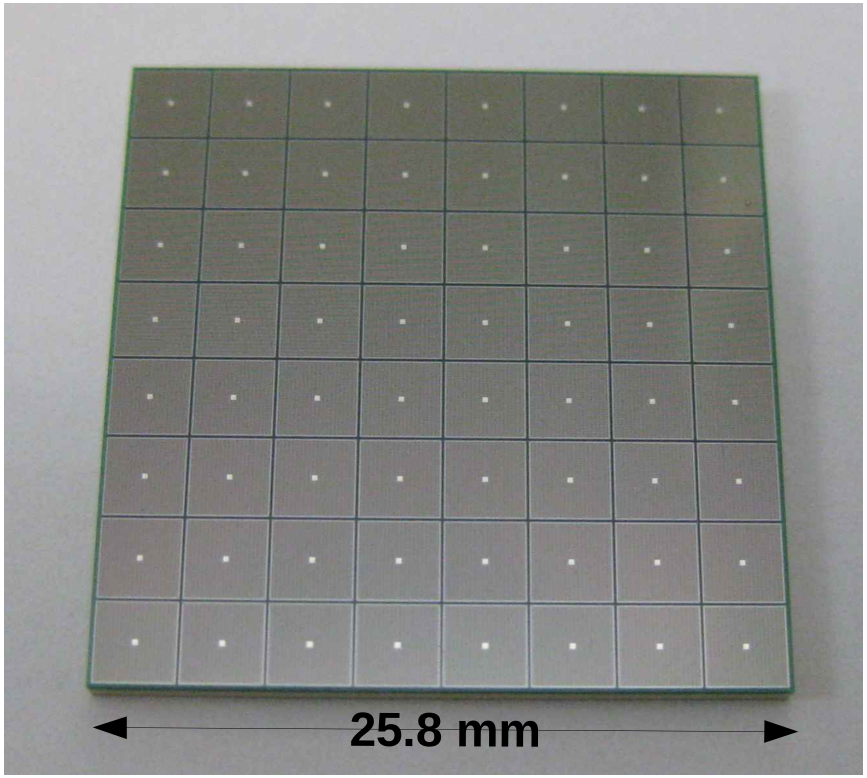
Article in preparation

From MACACO to MACACO II

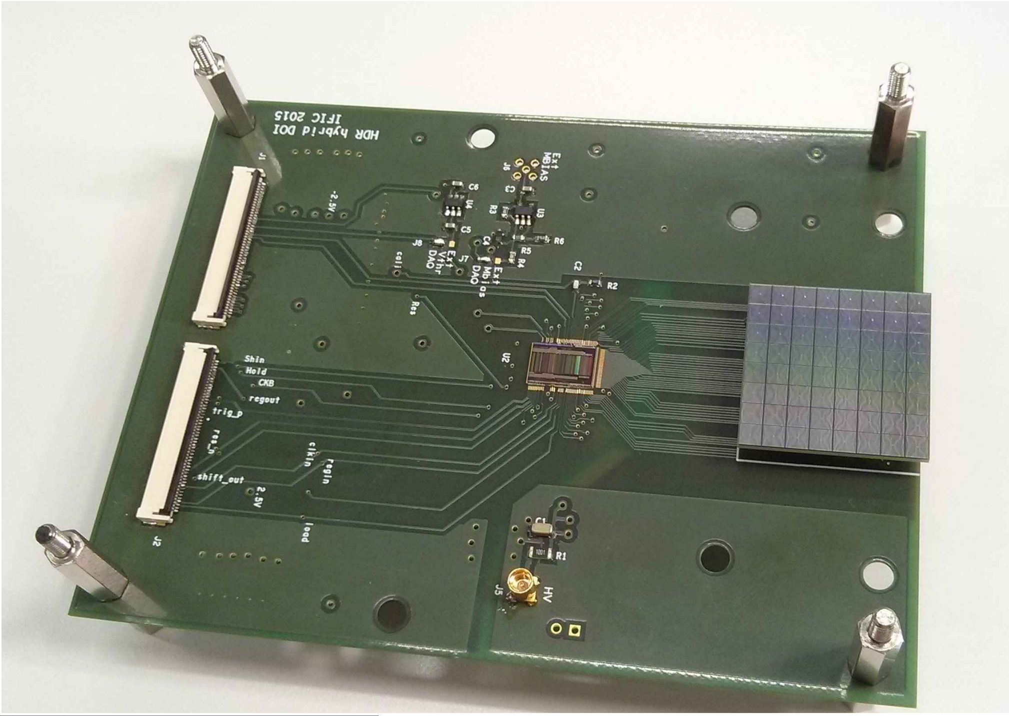
- System limitations: Energy resolution, timing resolution, electronics low dynamic range.
- New version:
  - New detectors to improve energy resolution.
  - Acquisition of two and three interaction events simultaneously with a new coincidences board.
  - New electronics?
  - Det 3 under development, 4 times larger

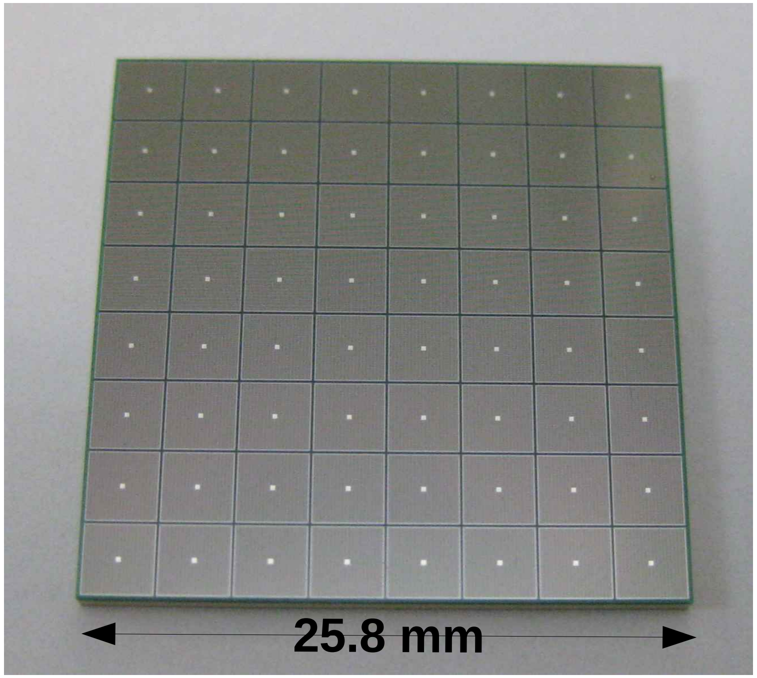
New photodetectors:
- TSV, 8x8 pixels.
- Better uniformity.
- Better PDE

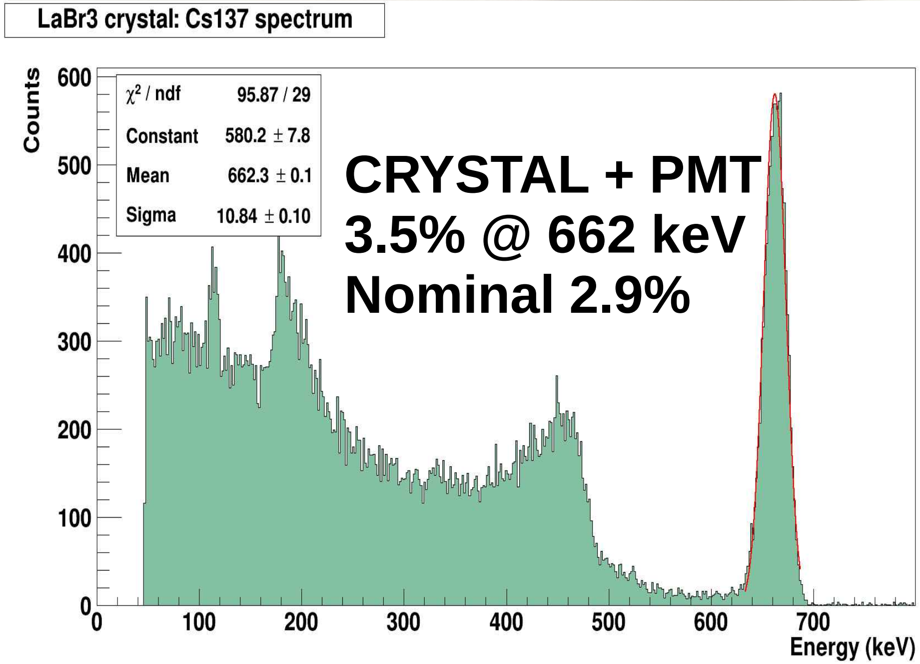
Hamamatsu S13361-3050AE-08



Second version of the system





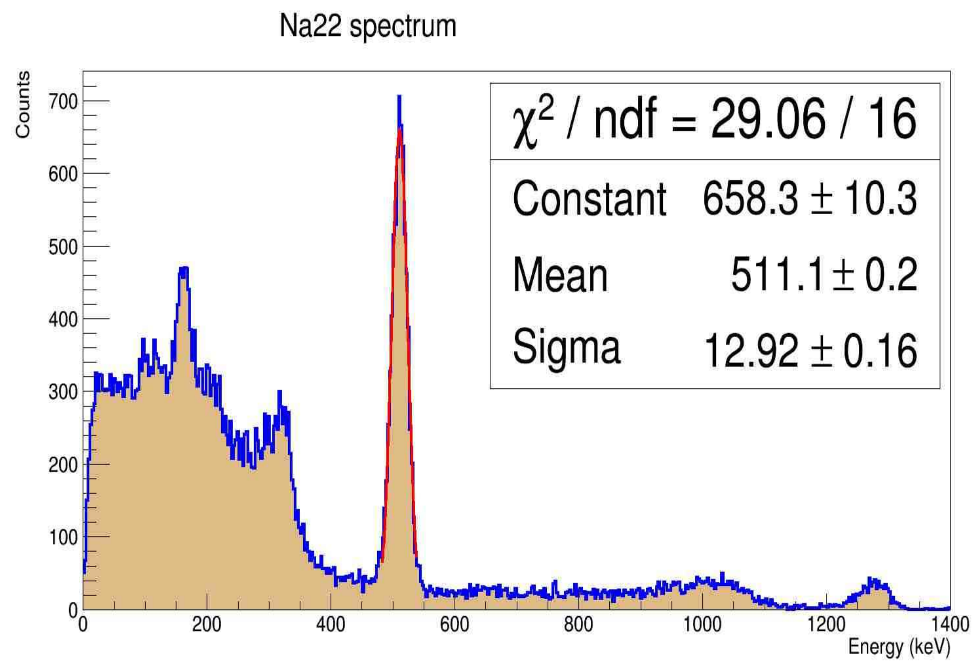


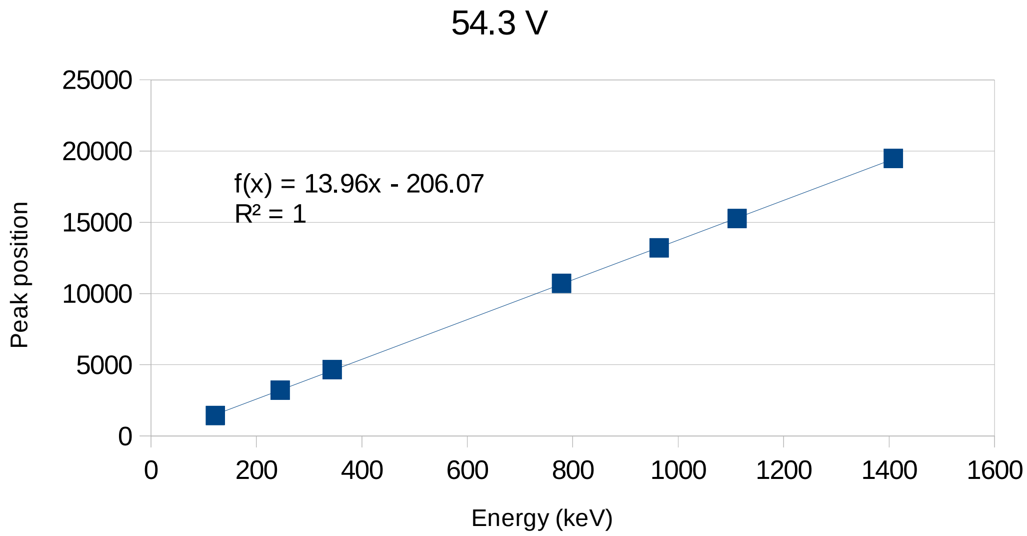
Linearity and energy resolution

CRYSTAL + SiPM array

ENERGY RESOLUTION

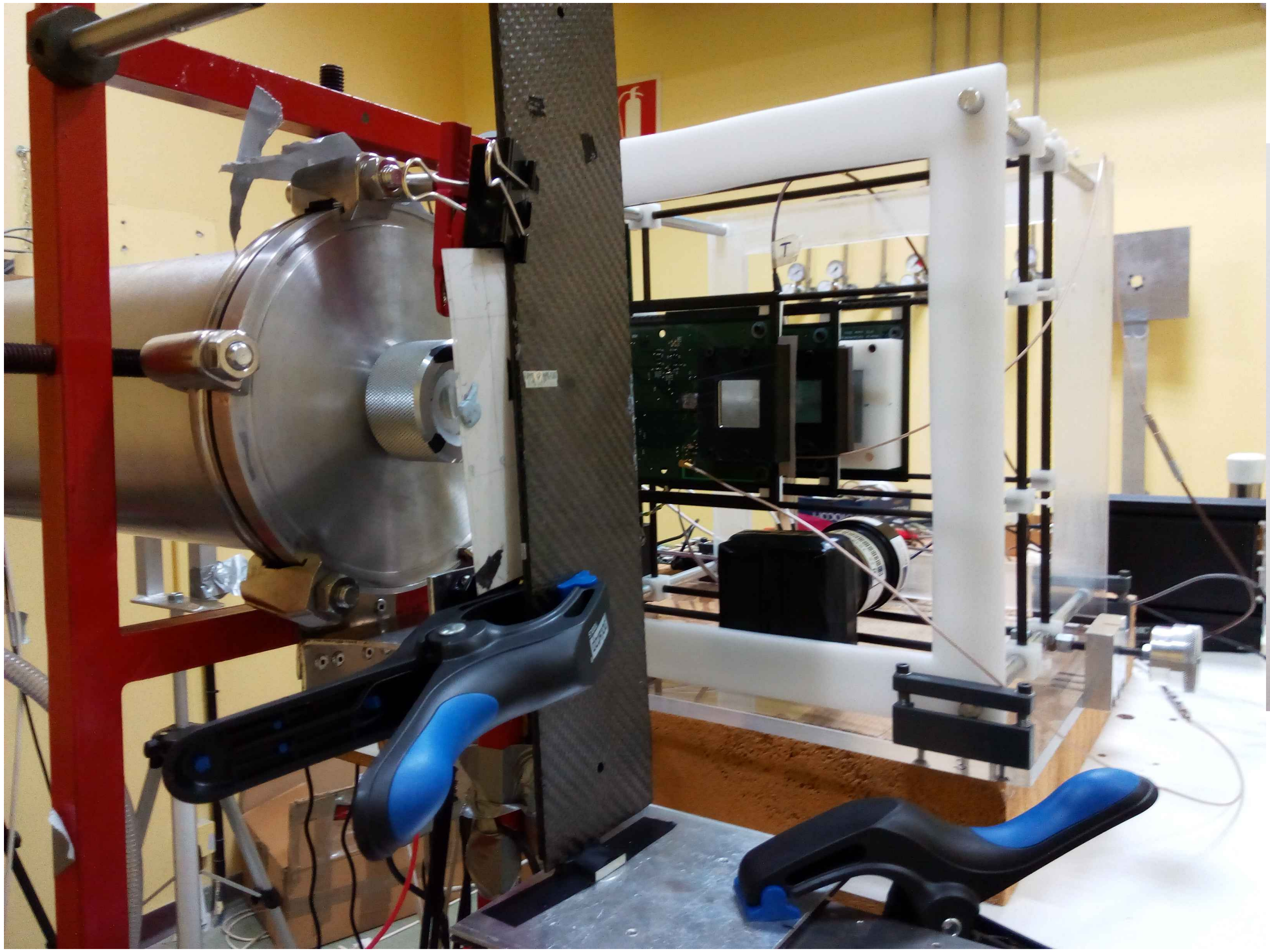
5.9% @ 511 keV @ 30ºC

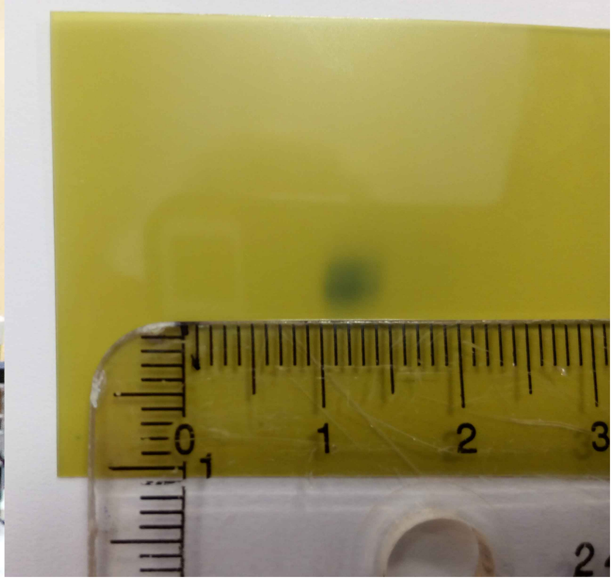




Tests at CNA

- Spanish National Accelerator Centre, Sevilla.
- 18 MeV protons on a graphite target → 4.4 MeV gamma rays.





Conclusions

- Final results obtained with MACACO I. Critical points identified.
- MACACO II is being assembled. First tests carried out.
  - Improved energy resolution.
  - Very promising first results.
  - Other improvements underway → Need to address application requirements.
- Need to carry out tests in clinical beams.

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Thank you! Questions?