Imaging of prompt gamma emissions during proton cancer therapy for geometric and dosimetric verification

Optimisation of Compton Camera system

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Proton Physics Research and Implementation Group workshop
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Overview

- **Advantages of protontherapy**

- **Methods of proton tracking**
  - ***β^+ emission***
  - ***Prompt γ emission***
    - *Prompt γ imaging methods*

- **Pulse Shape Analysis to localise the proton range**
  - ***Reconstruction code***
  - ***Spin-off of AGATA technology***
  - ***Prospectus + third layer (GRI+)***

- **Optimisation of Compton Camera system**
  - ***Simulation with GAMOS***
  - ***Tests with sources at the University of Liverpool***

- **Perspectives for the project**
  - ***Measurements of radiation and neutron background at the Clatterbridge cancer centre***
  - ***Improving the image reconstruction code (Poster: Andrea Guttierrez UCL)***
  - ***Measurements in realistic conditions at Clatterbridge cancer center***

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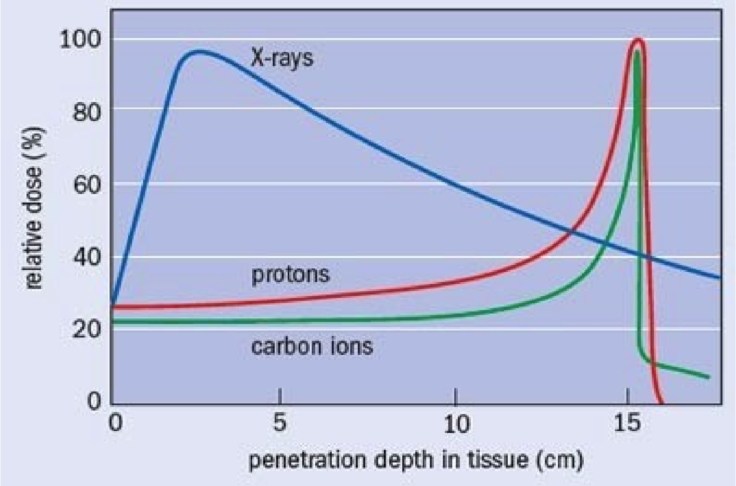
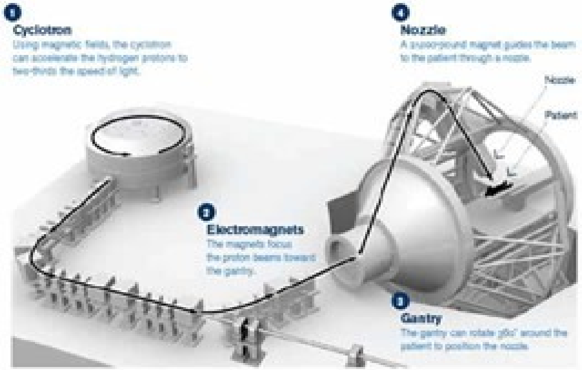
Protontherapy: advantage and limit



Deposited energy vs penetration depth

Advantage comparing with photontherapy

- Proton → **sharp Bragg Peak**
- Radiation dose close to tumour dimension, sparing surrounding normal tissues
- Very suitable for childhood cancers (increasing success rate and reducing side effect)
- The demand for proton therapy as cancer treatment has being growing during last decade
- Only one protontherapy centre in United Kingdom: **The Clatterbridge Cancer Centre**
- United Kingdom would like to build two new protontherapy centres:
  - ➔ **Christie Hospital** at Manchester (Talk M.J. Merchant)
  - ➔ **University College London Hospital**
- However, **uncertainties** can lead to serious adverse efects
  - ➔ ***in-vivo* proton range verification during therapy**



Protontherapy centre at Christie

Proton tracking: β^{+} and prompt γ emission

- **Nuclear interaction in proton therapy creates a lot of secondary products:**

  - **β^{+} emitting isotopes**
    - Two 511 keV γ → Positron Emission Tomography → Proton range
    - 1-2 mm accuracy in well-coregistered bony structure
      Parodi K et al (2007b) Int. J. Radiat. Oncol. Biol. Phys. 68 920–34
    - **In general** verification accuracy is around **5-10 mm**
      Knopf A C et al (2011) Int. J. Radiat. Oncol. Biol. Phys. 79 297–304
    - Simulations need to be **corrected for biogical washout**
    - **Relevant cross-section no know** for isotope production in tissues (no thin target)

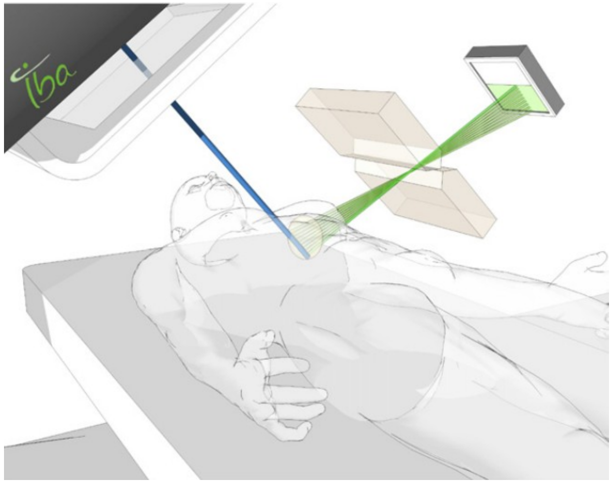
  - **Prompt γ emission**
    - Lack of biological washout
    - **Higher γ-prompt production rate** than 511keV production rate (at least 10 times higher)
      Moteabbed M, España S, Paganetti H. Phys Med Biol (2011) 56:1063-82
    - PG distribution is closer to the dose falloff than the PET distribution
    - Prompt γ has high energy → **Low detection efficiency**
    - Need to develop **an algorithm for 3D dose reconstruction**

Prompt γ imaging

- **Slit camera**
- ➔ Need to use a collimator
  - ➢ Low statistics
- ➔ 1D distribution
- ➔ **1-2 mm** standard deviation on range estimation

J.Smeets et al 2012 Phys. Med. Biol. 57 3371

Example of slit camera



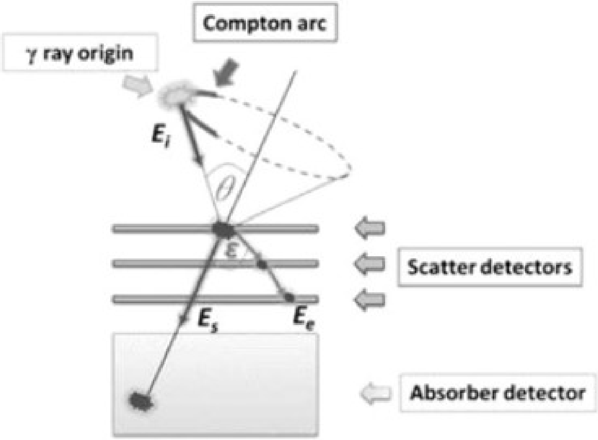
J.Smeets et al 2012 Phys. Med. Biol. 57 3371

- **Compton camera**
- ➔ 2D or 3D distribution
- ➔ Coincidence between the different layers
  - ➢ Low statistics

- 6 DSSD + $LaBr_3$:Ce scintillator
- ➢ Electron tracking → only Compton arc
- ➢ Spatial resolution of **5.5 mm**

P.G.Thirolf et al. EPJ Web of conferences 117, 05005 (2016)

- 2 High-Pure Germanium detector + Ge coaxial detector
- ➢ Correct efficiency of Ge with high E γ-rays
  - ➢ Statistics can balance the absence of electron tracking
- ➢ Pulse Shape Analyse can give very precise position of interaction



P.G.Thirolf et al. EPJ Web of conferences 117, 05005 (2016)

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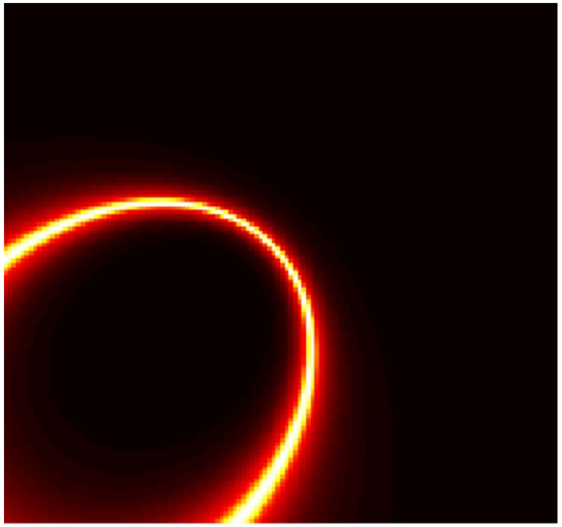
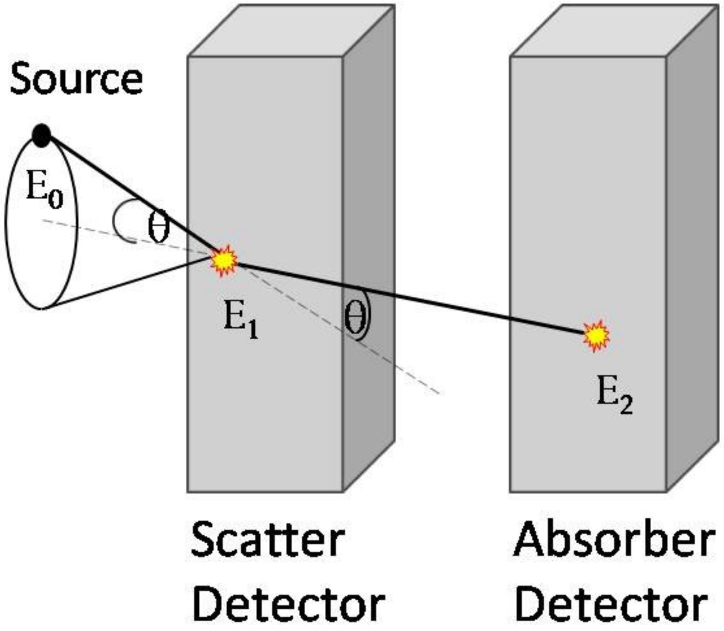
Image reconstruction code

Analytic reconstruction code created by **Dr. D. Judson (University of Liverpool)**
Method: use of geometrical properties of conic sections

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





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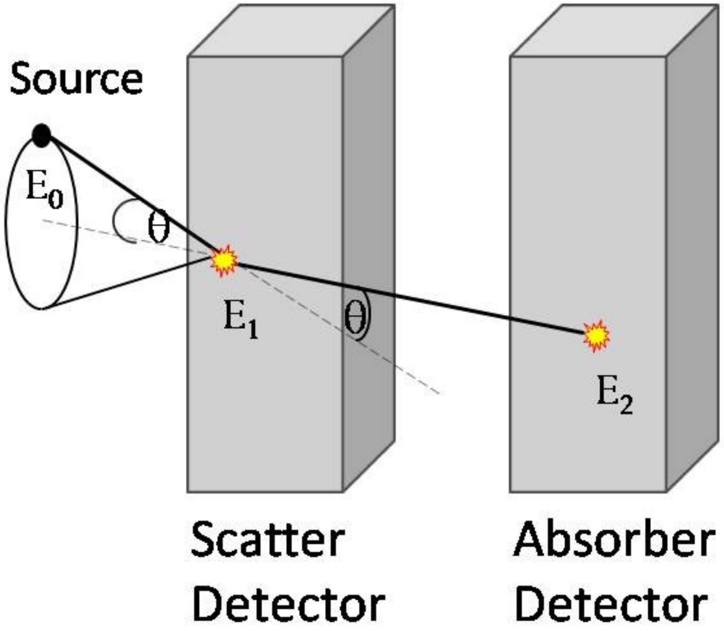

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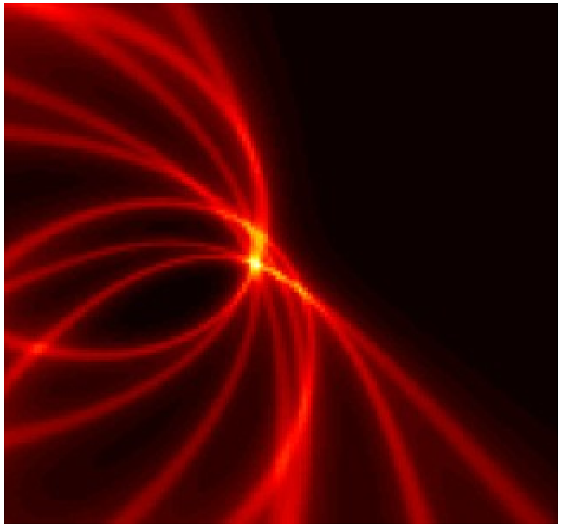
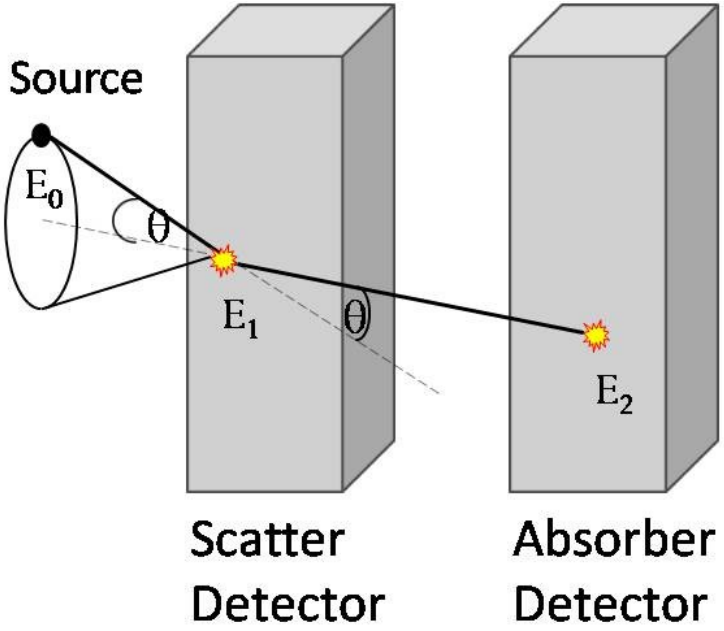
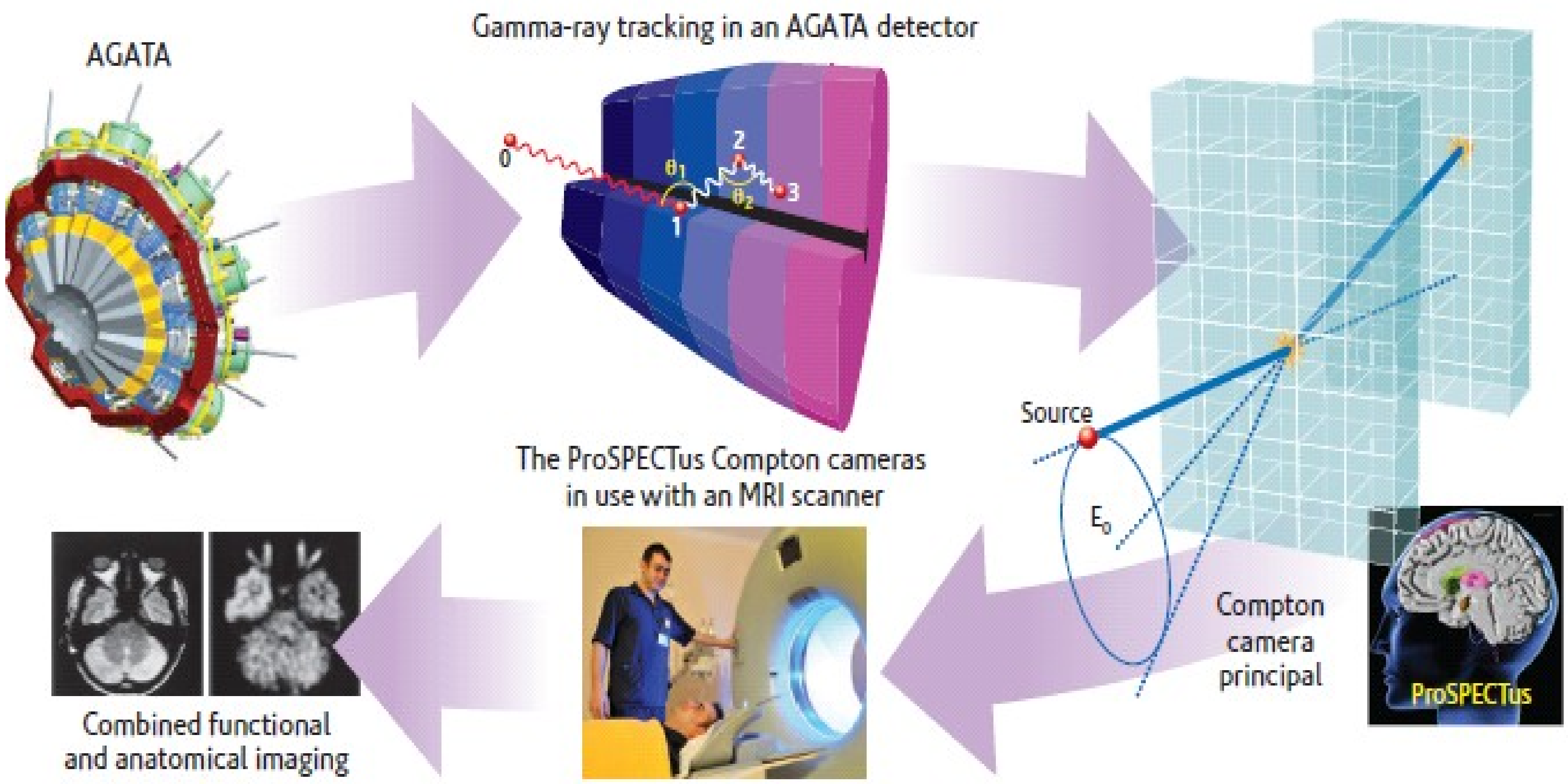




Pulse Shape Analysis: Spin-off of AGATA

Technology transfer from fundamental nuclear physics to medical physics



Ideal case: Pulse Shape Analysis can give a **1mm^3 precision**

R.J. Cooper et al. NIM A 573(2007) 72-75

AGATA: Advanced Gamma Tracking Array

SPECT: Single Photon Emission Computed Tomography

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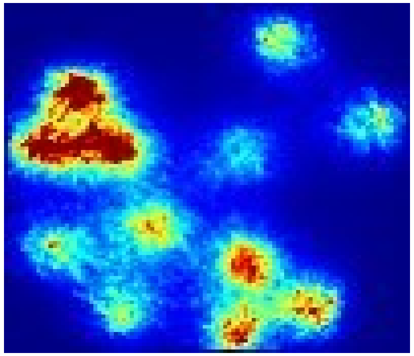
Prospectus

- First application of AGATA technology PSA in medical physics
- Scatterer SiLi and Absorber HPGe in one cryostat
- Detector head sensitivity maximised for ^{99m}Tc (141 keV γ) and works also for ^{131}I (364 keV γ)
  - ➔ **Wild energy range** with one system
- **Sensitivity is 10 times higher** than LEHR collimated SPECT detector heads
- Position resolution is around **2-3 mm**
- MRI-compatible
  - ➔ Anatomical and Functional Imaging
- *L.J.Harkness et al.(2010) IFMBE proceedings 25(2):102-105*

phantom



Imaging reconstruction

LEHR: Low Energy High Resolution

SPECT: Single Photon Emission Computed Tomography

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Prospectus + third layer (GRI+)

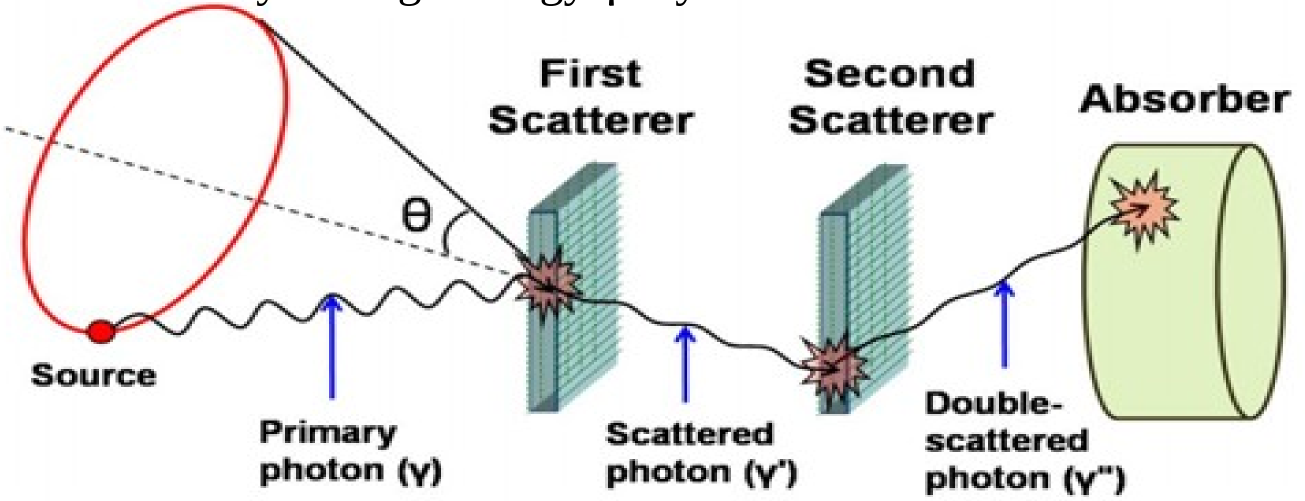
- Imaging to check the entended proton treatment delivery
  - Geometrical placement of the beam (range verification)
  - Verification of delivered radiation dose

- Prompt γ energies:
  - $^{12}C(p,p)^{12}C^*$: 4.4 MeV
  - $^{16}O(p,p)^{16}O^*$: 6.0 MeV

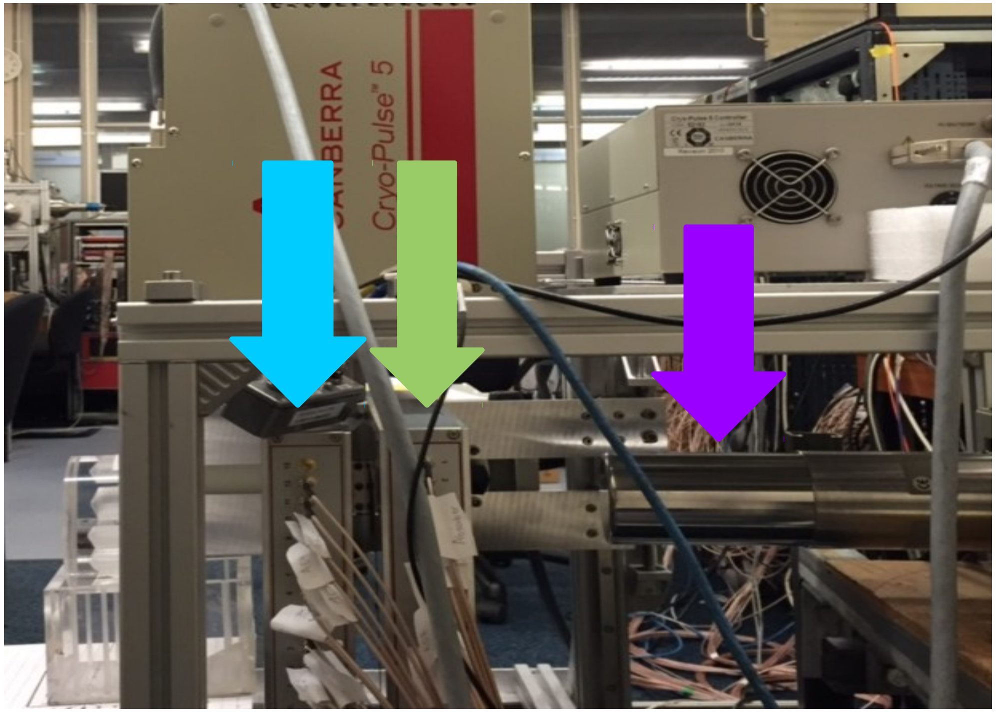
- Neutron capture by proton:
  - p(n,γ)d : 2.2 MeV

- Need a third layer to know the energy of the incoming γ-rays

- Low detection efficiency for high energy γ-rays



Prospectus + third layer (GRI+)



- Three layers Compton System:
  - ➔ Si(Li) detector as the first scatterer detector
  - ➔ High-Pure Ge detector as the second scatterer detector
  - ➔ Coaxial germanium detector as the absorber detector

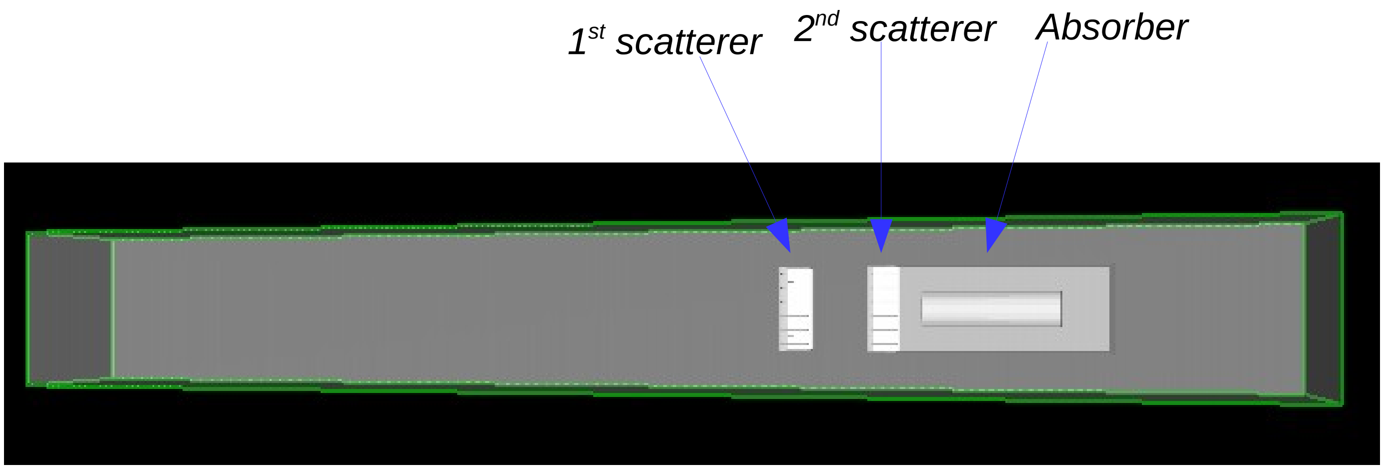
- A full triple layers Canberra Compton Camera

Simulation using GAMOS

Geant4-based **A**rchitecture for **M**edicine-**O**riented **S**imulations

P. Arce et al. NIM A 735(2014)304-313

L.J. Harkness et al. NIM A 671(2012)29-39 (Compton Camera part)



- 2 HPGe detectors 60x60x20 mm^3 (5x5x20 mm^3 granularity)
- Ge coaxial detector

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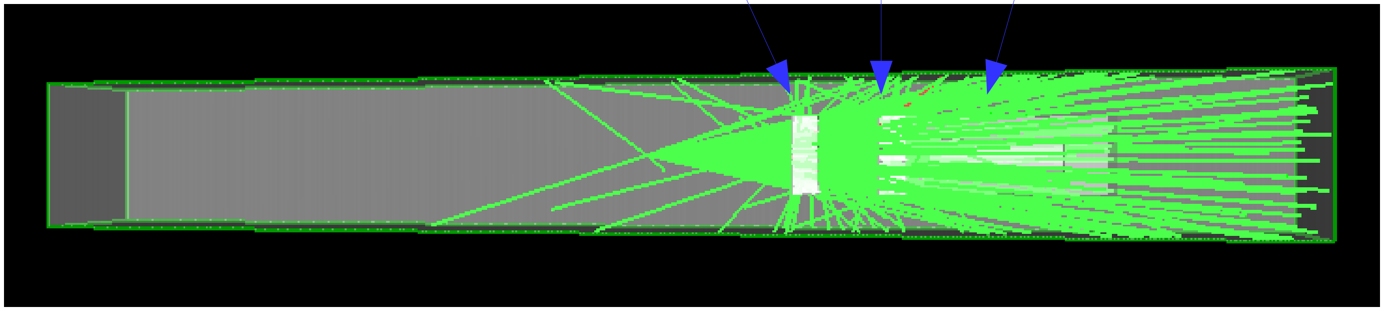


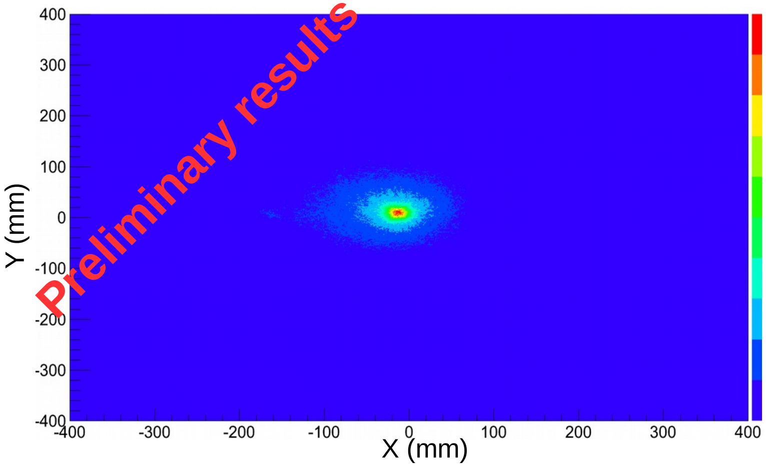
- 1.836 MeV γ-rays cone emission simulation
- 5 keV energy resolution (experimental measurement)

Measurements at the University of Liverpool

- Measurements were performed by **L.Thomas** and PhD students in November 2016

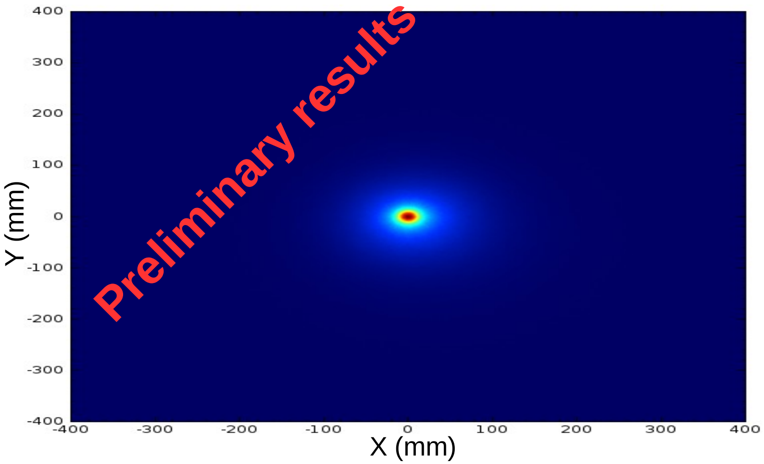
^{88}Y source

Measurements



FWHM: 23.07 ± 0.59 mm

GAMOS Simulation ***5x5x20***



FWHM: 24.34 ± 0.13 mm

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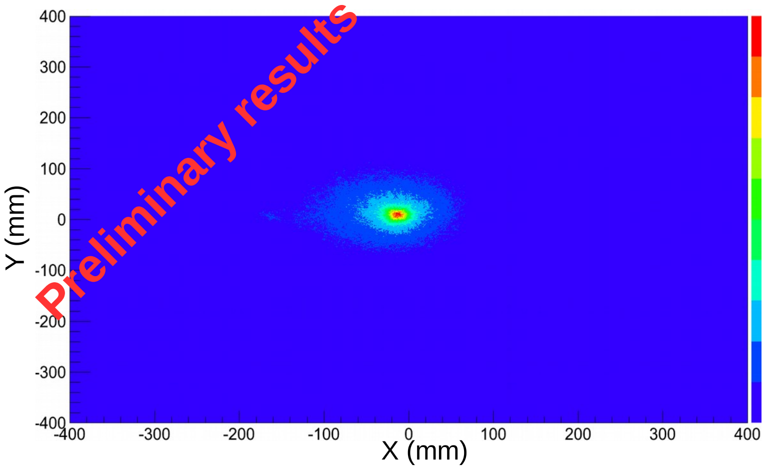
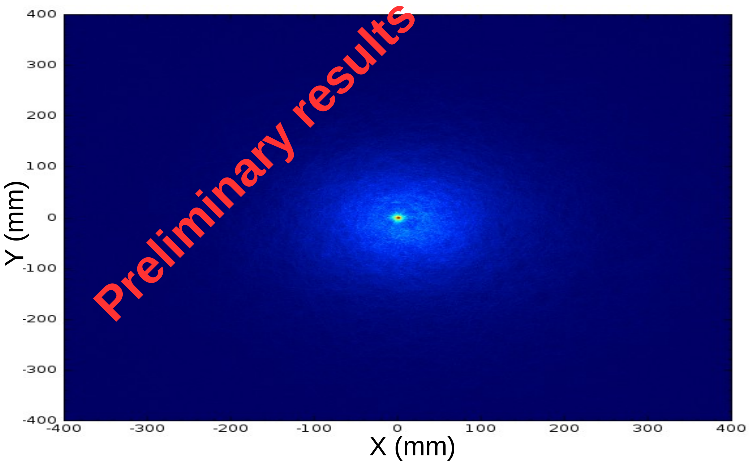


GAMOS Simulation ***1.25x1.25x5***



FWHM: 23.07 ± 0.59 mm

FWHM: 6.44 ± 0.39 mm

- If we use the Pulse Shape Analysis

➔ Need to study the electric field behaviour in the detector

Perspectives for the project

- The set-up and the acquisition system are working well
- Simulations and measurements are very close → Confidence in the GAMOS simulation
- PSA should permit to have a precision better than 6.5 mm

<u>Current work</u>

- Improving Reconstruction Code (iterative code) by **Dr Andrea Gutierrez** (UCL)
- Keeping analysing data measurements performed last November (^{88}Y and ^{60}Co)
- Improving simulations including more details about the proton beam and the set-up
- Study of electric field behaviour in detectors to use PSA

<u>Expected planning</u>

- Radiation and neutron background measurements at Clatterbridge cancer centre in January 2017
- Measurements using the Compton Camera system at Clatterbridge cancer centre in summer 2017

Collaboration

- **Nuclear Physics group, Department of Physics, University of Liverpool, UK**
  Benjamin Le Crom, Leya Thomas, Andrew Boston

- **Medical Physics Department, The Royal Berkshire NHS Foundation Trust, UK**
  Colin Baker

- **Department of Medical Physics and Biomedical Engineering, University College London, UK**
  Andrea Gutierrez, Robert Moss, Robert Speller

- **National Centre for Eye Proton Therapy, The Clatterbridge Cancer Centre NHS Foundation Trust, UK**
  Andrzej Kacpereck

Thank you for your attention

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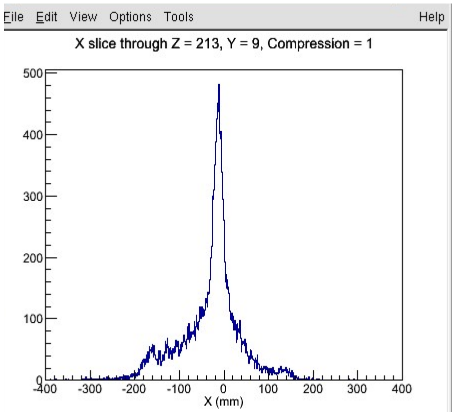
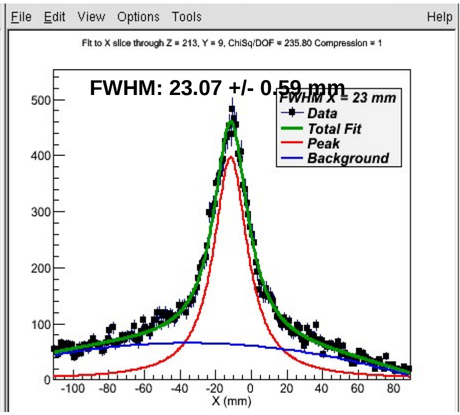
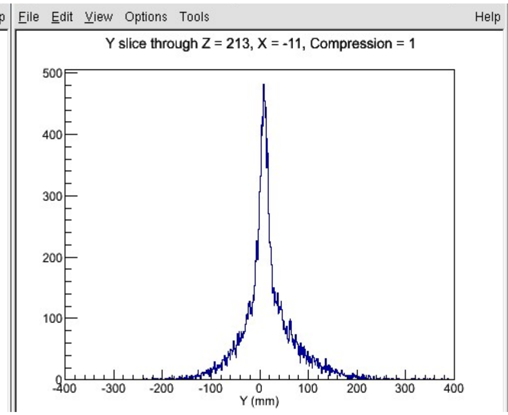
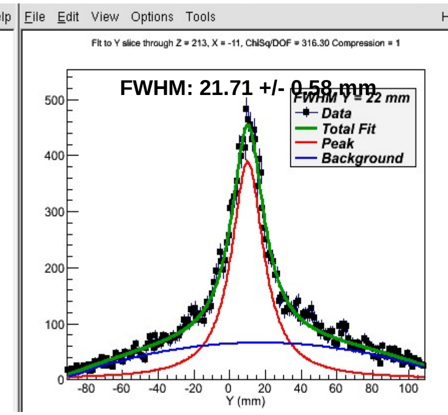
Different fits

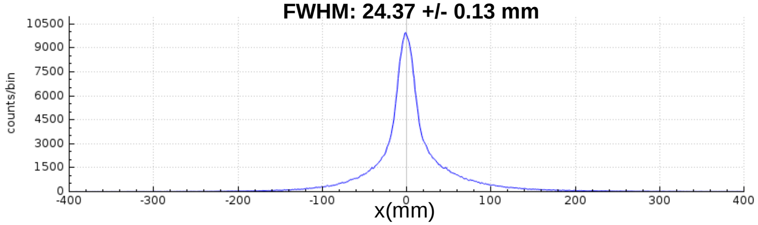




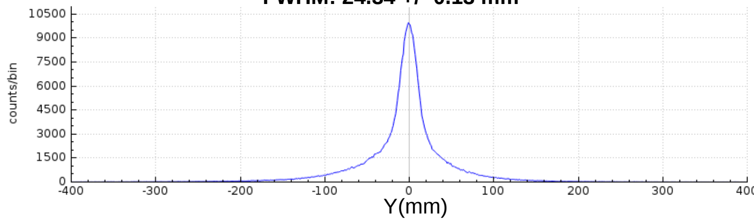




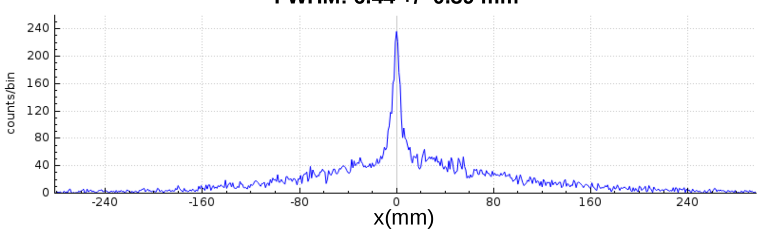
FWHM: 24.37 +/- 0.13 mm



FWHM: 24.34 +/- 0.13 mm

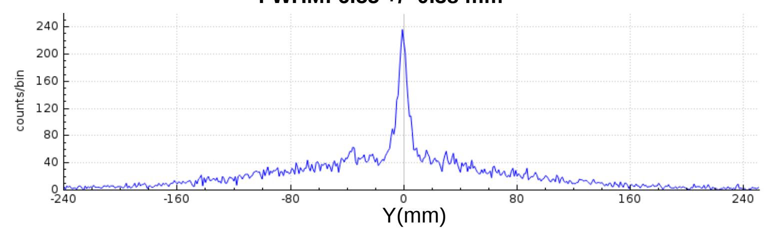


FWHM: 6.44 +/- 0.39 mm



PSA

FWHM: 6.55 +/- 0.38 mm



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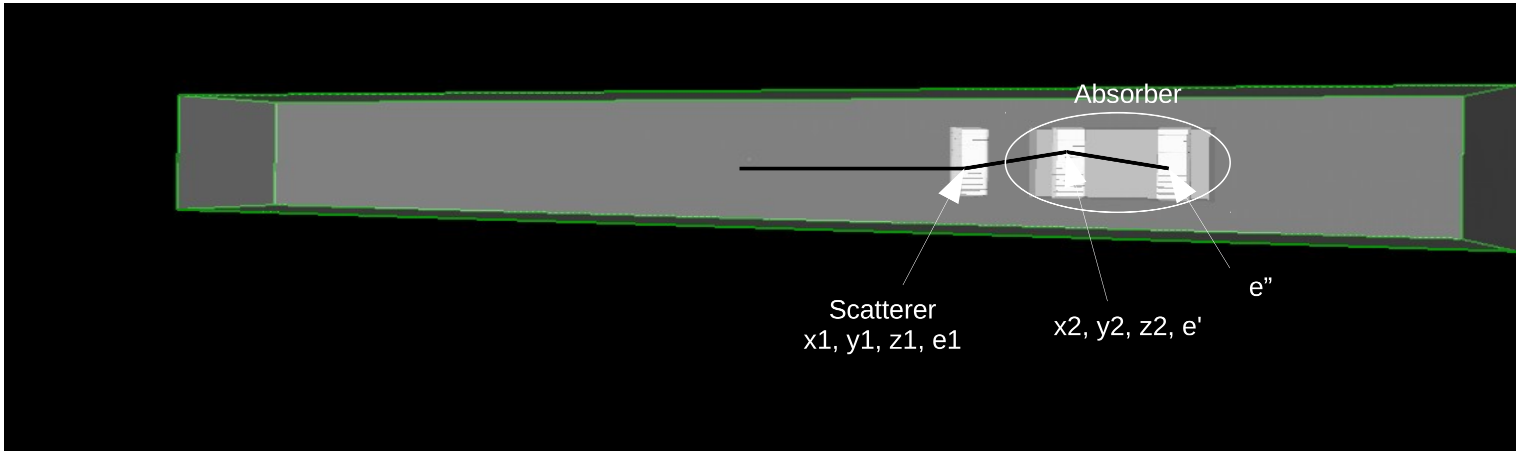
GAMOS output



Output:
COMPCAM x1 y1 z1 e1 x2 y2 z2 e2

e2 = e' +e''