A Spectroscopic Study of Prompt Gamma Emission for Online Range Verification in Proton Therapy

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Contents

Introduction to Ion Therapy and Prompt Gammas

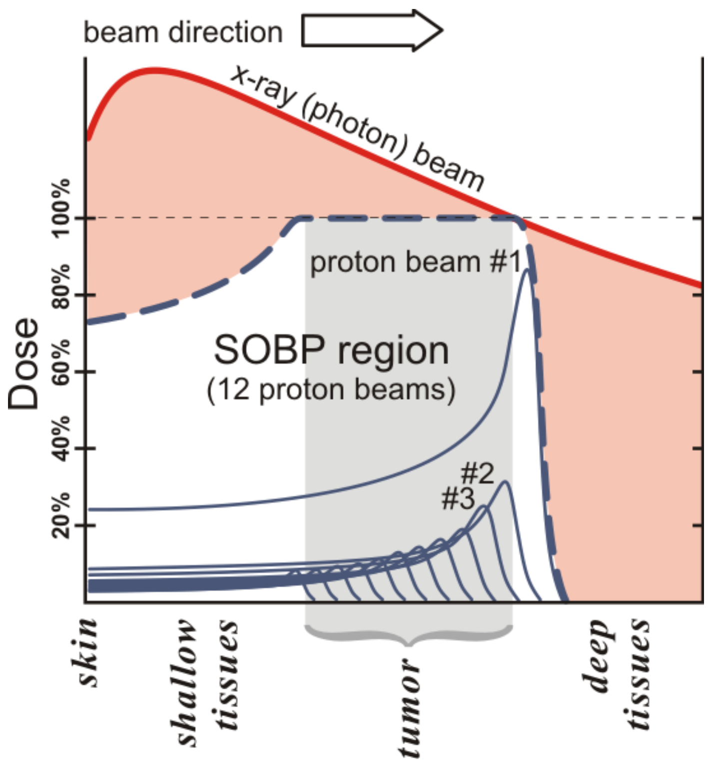
Setup at Test Beam Time at HIT

Analysis of Prompt Gamma Spectra

Conclusion and Outlook

Introduction to Ion Therapy

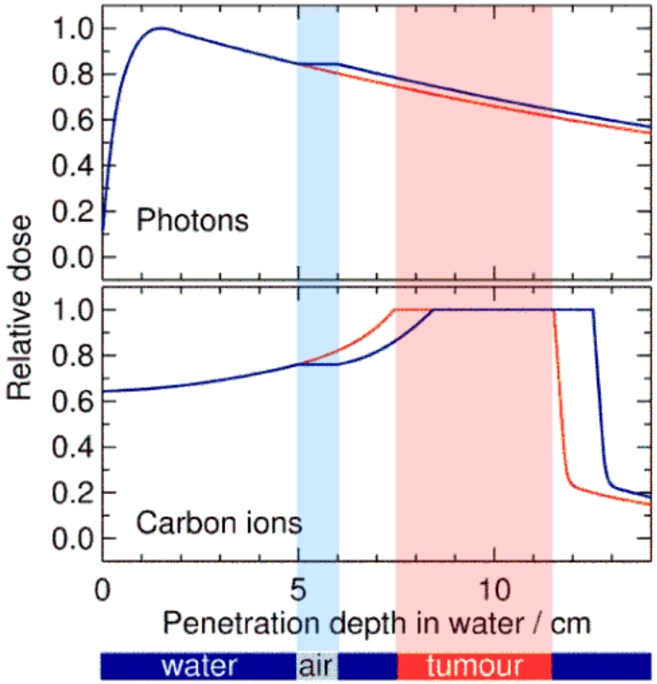
- Radiation therapy is one important method to treat malignant tumors
- Advantages of ion therapy comparing to x-rays:
  - Biological effectiveness: Double-strand breaks (heavy ions only)
  - Physical: Dose distribution (all ions)



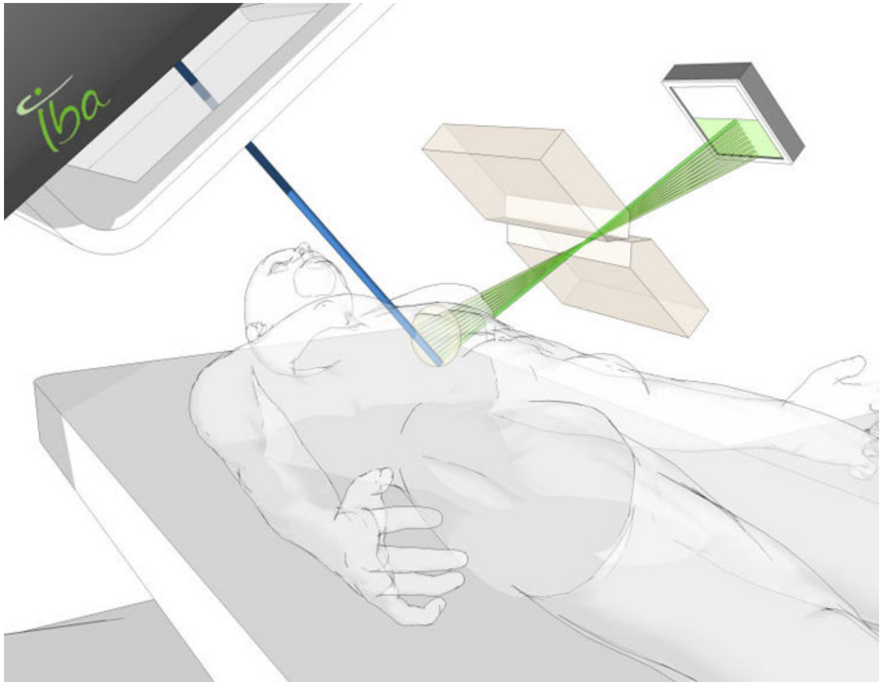
Dose distribution of different radiation typesLevin et al (2005): “Proton beam therapy”. In: British Journal of Cancer.

Need for On-line Range Verification

- Steep slope after Bragg Peak makes ion therapy susceptible for range errors
- Today: In-beam PET after irradiation
- Future: On-line beam monitoring desired
- Approach: Prompt gammas emitted during ion therapy



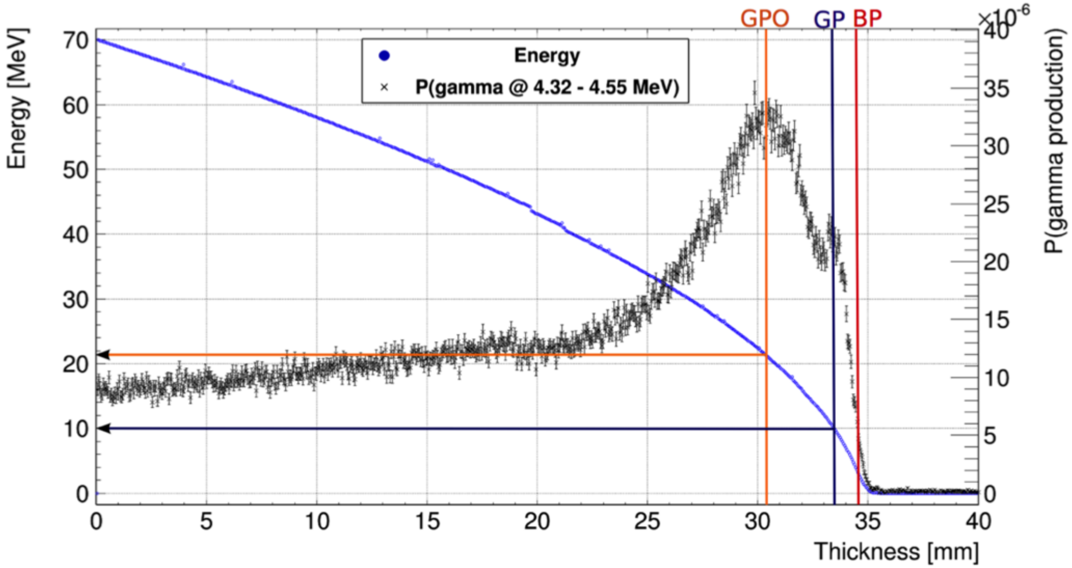
Density effect on x-ray and carbon ion dose distribution
HZDR, https://www.hzdr.de/db/Cms?pOid=11326&pNid=158



Prompt gammas emitted during ion therapy used for online beam monitoring
http://medicalphysicsweb.org/cws/article/research/49909

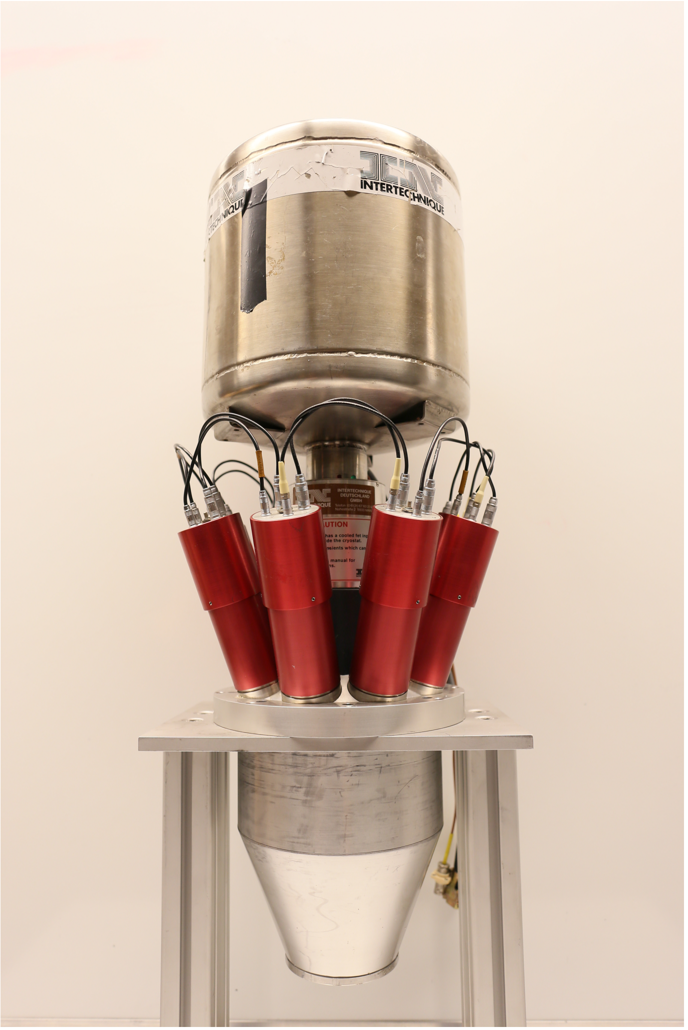
Introduction to Prompt Gammas

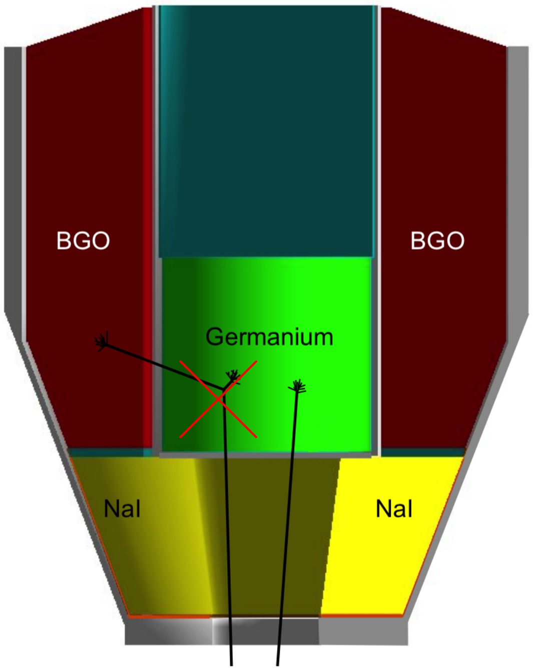
- Prompt gammas are emitted by nuclear reactions
- Cross section of prompt gamma emission is proton-energy dependent
- Far goal: On-line range verification device for ion beams, e.g. Compton camera
- First phase: Study prompt gamma emission using High-Purity Ge detector



GEANT4 Simulation of 4.4 MeV prompt-gamma emission in PMMA (Sabine Feyen)

HPGe Detector with Active Compton-Shield

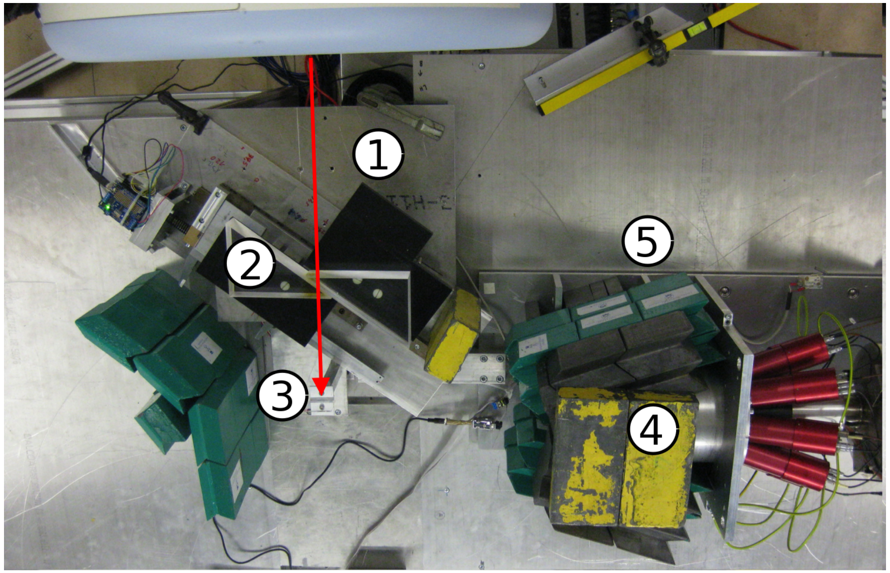




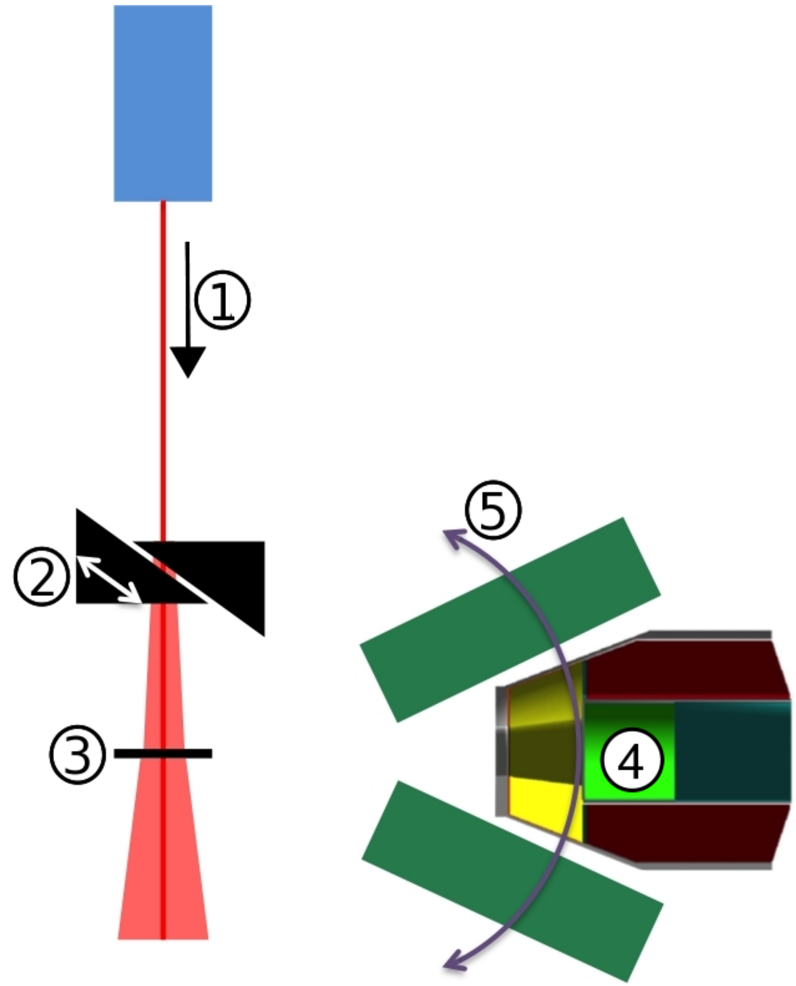
High-Purity Germanium Detector:

- Energy resolution better than 2 keV @ 1 MeV
- Surrounded by Active Compton-Shield (ACS) in order to reject Compton events

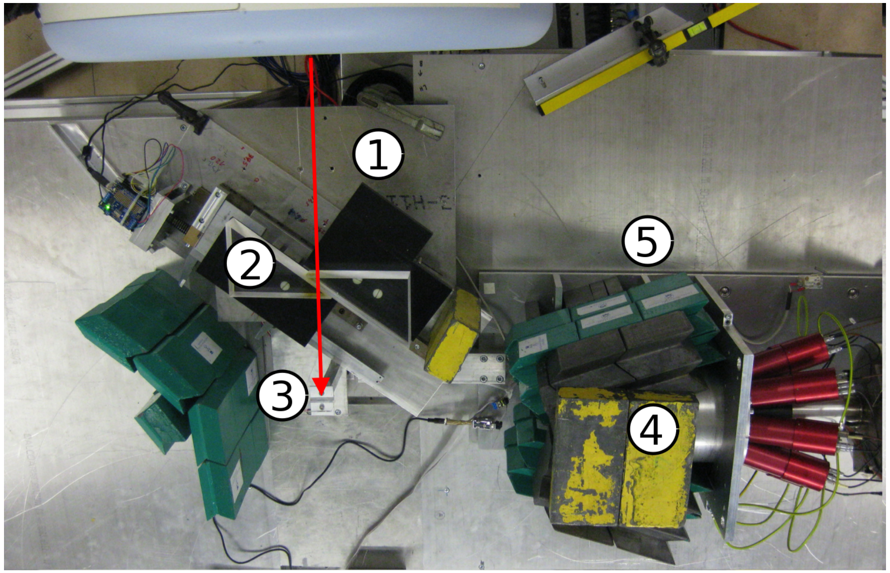
Setup during Test Beam at HIT 2015

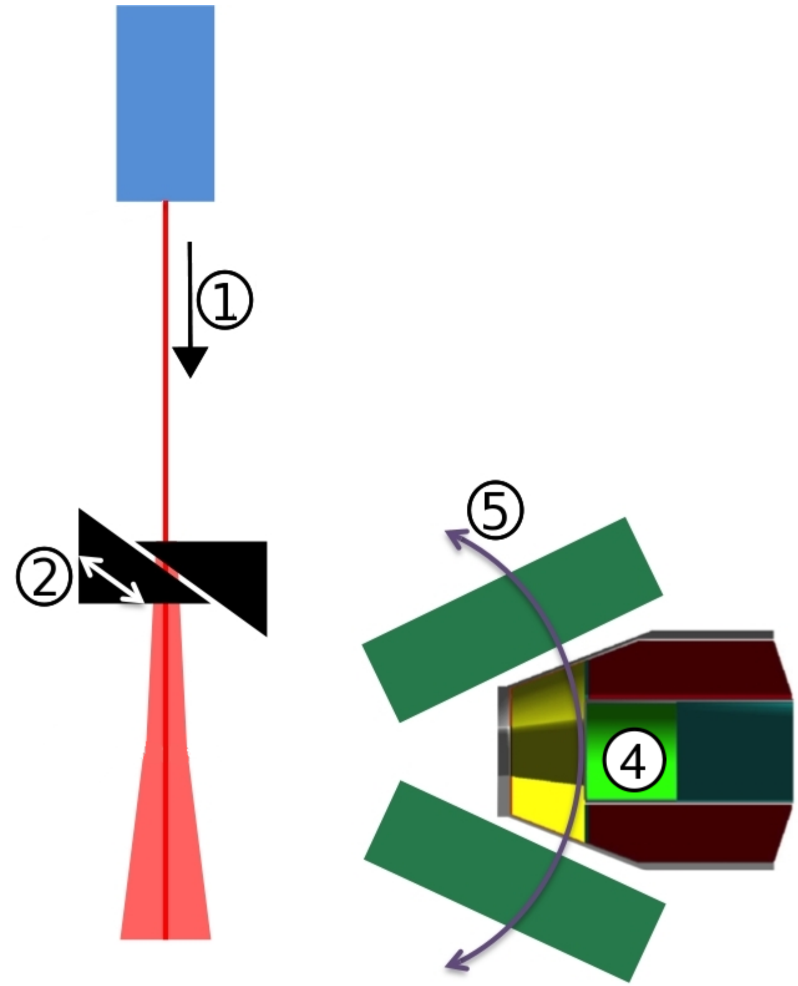


1 Proton pencil beam (70 and 130 MeV)
2 Adjustable target thickness (**wedges**)
3 Thin target **slice**
4 HPGe detector to measure prompt gamma radiation from thin slice
5 Detector rotation system



Setup during Test Beam at HIT 2015





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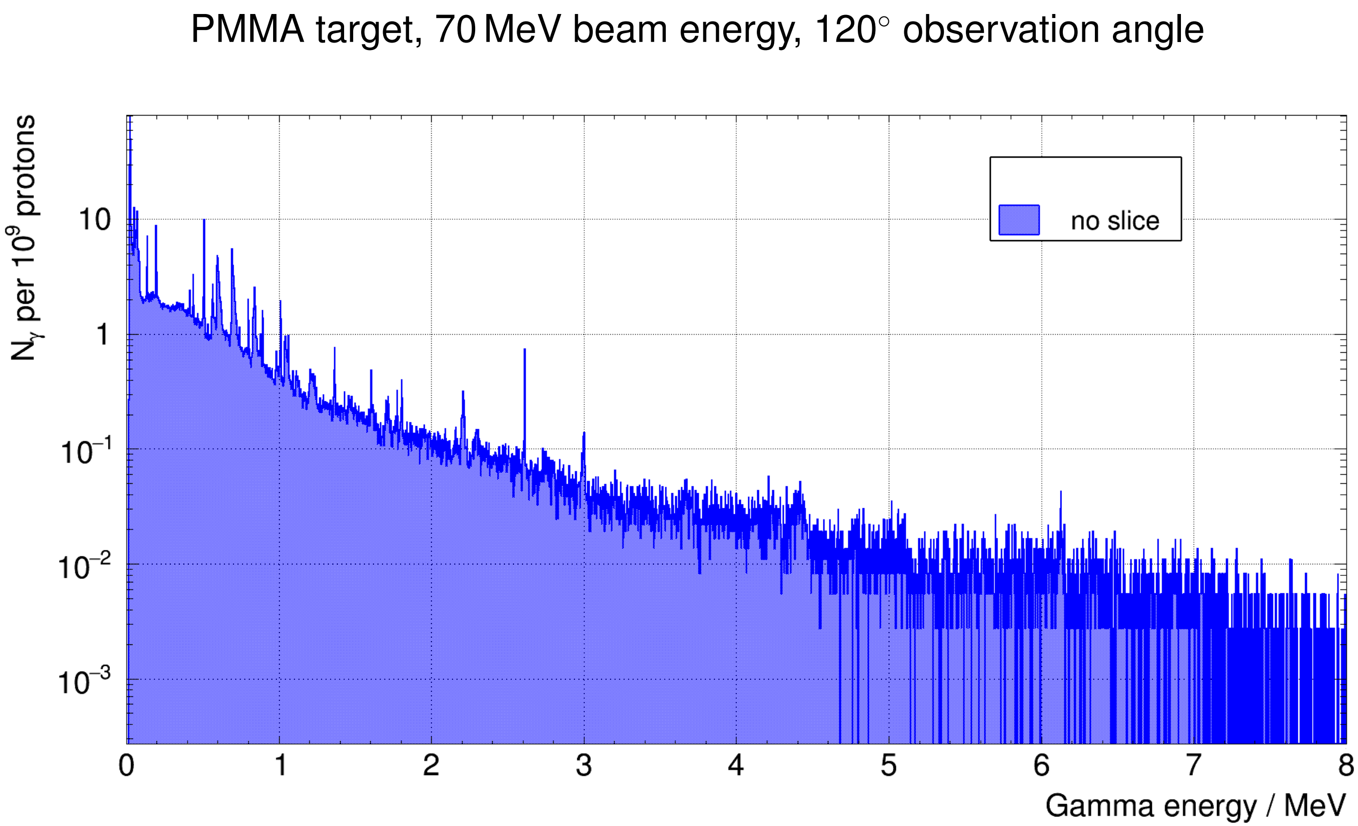
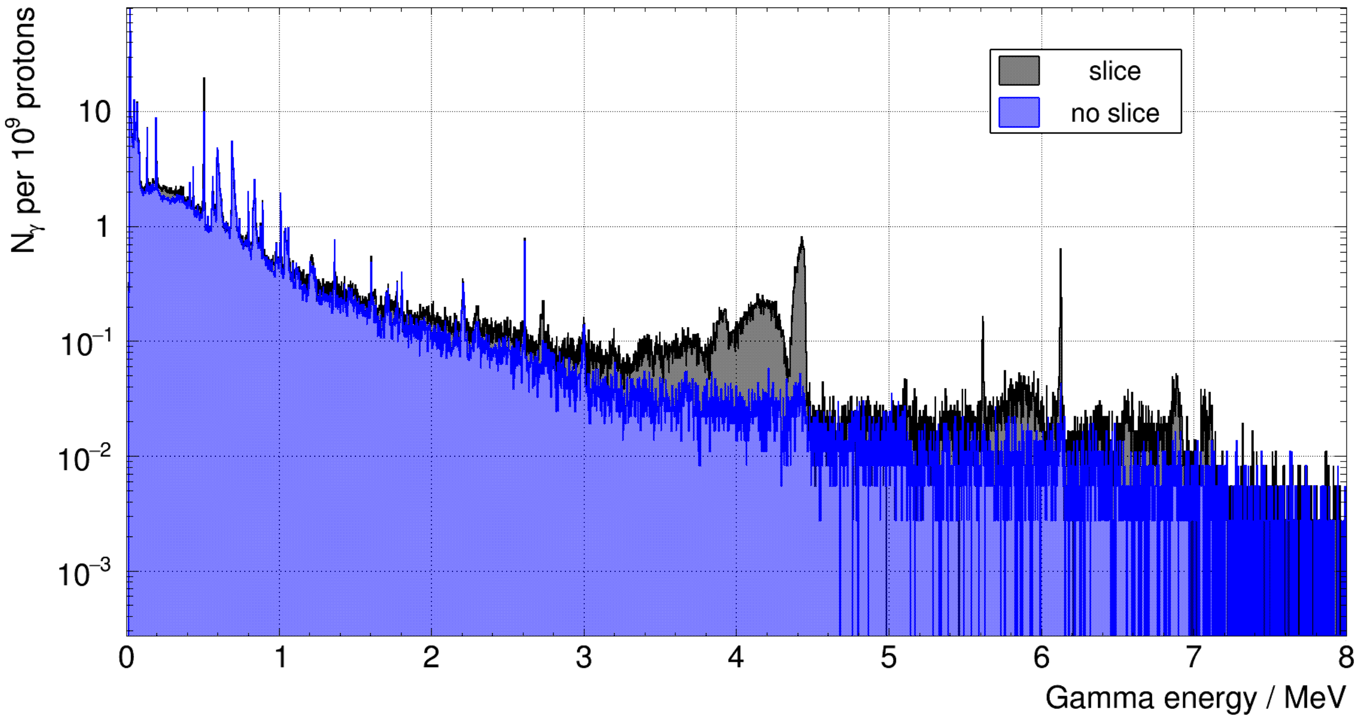
Gamma Spectrum



- Background measurement (blue): Measurement **without slice** in beam path

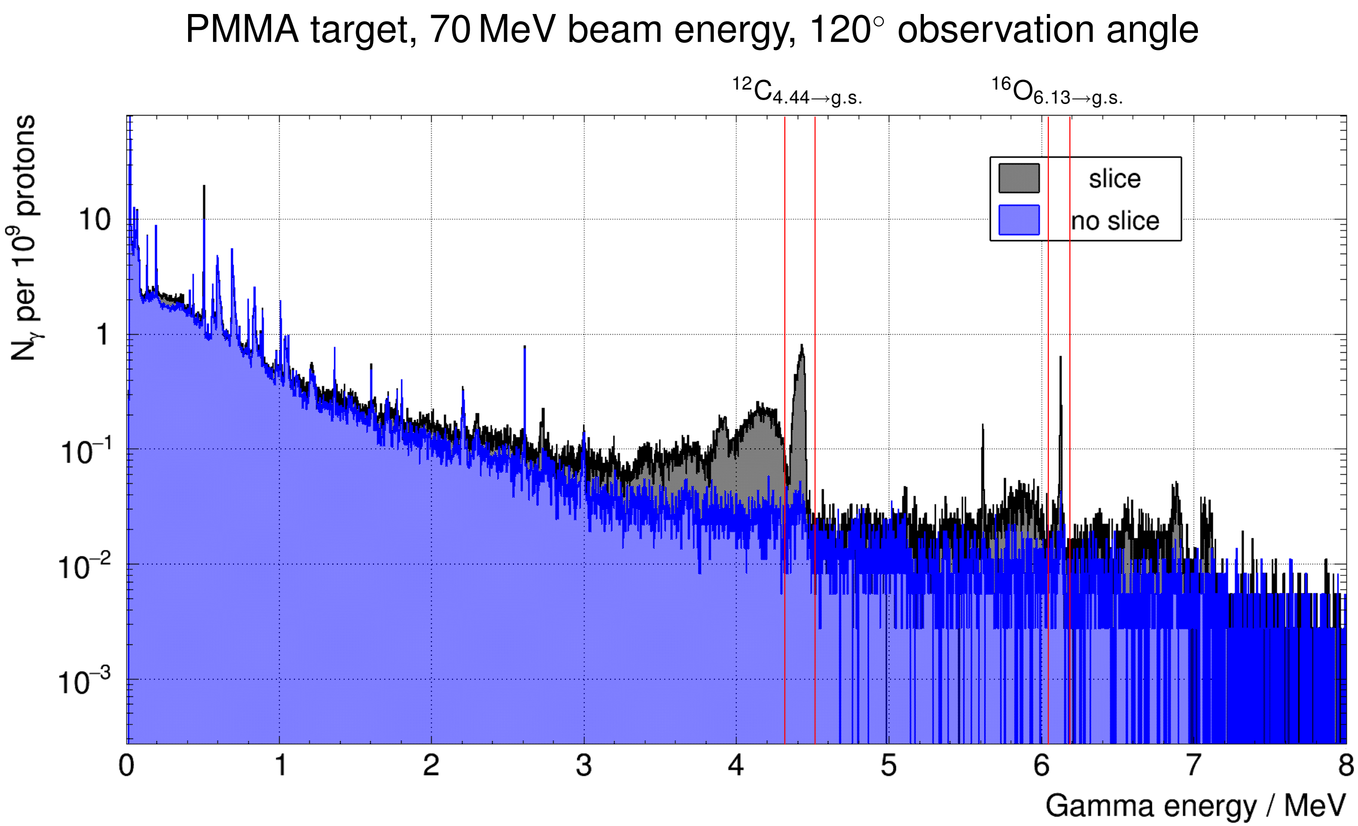
Gamma Spectrum

PMMA target, 70 MeV beam energy, 120° observation angle



- Background measurement (blue): Measurement **without slice** in beam path

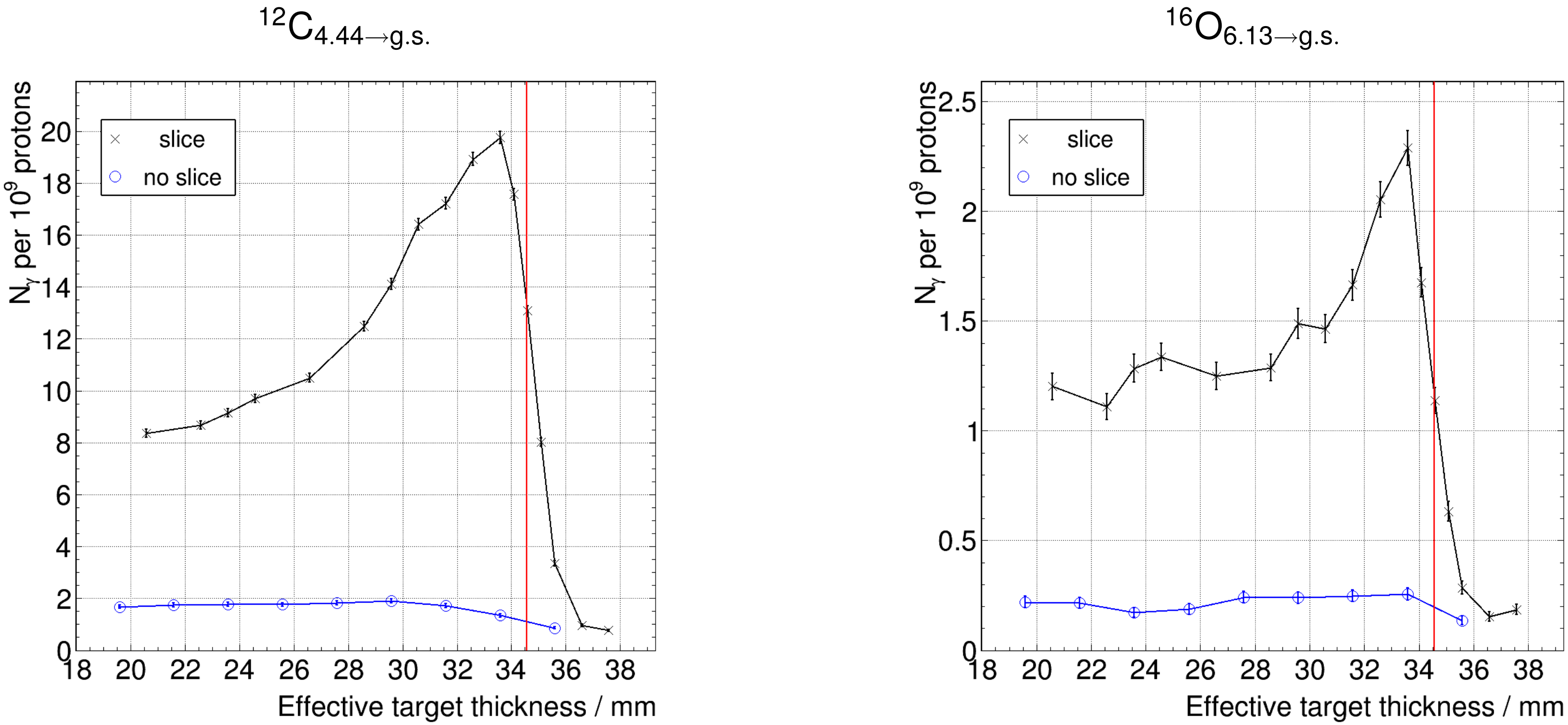
Gamma Spectrum



- Background measurement (blue): Measurement **without slice** in beam path
- Gamma yield = Integral of prompt gamma peak

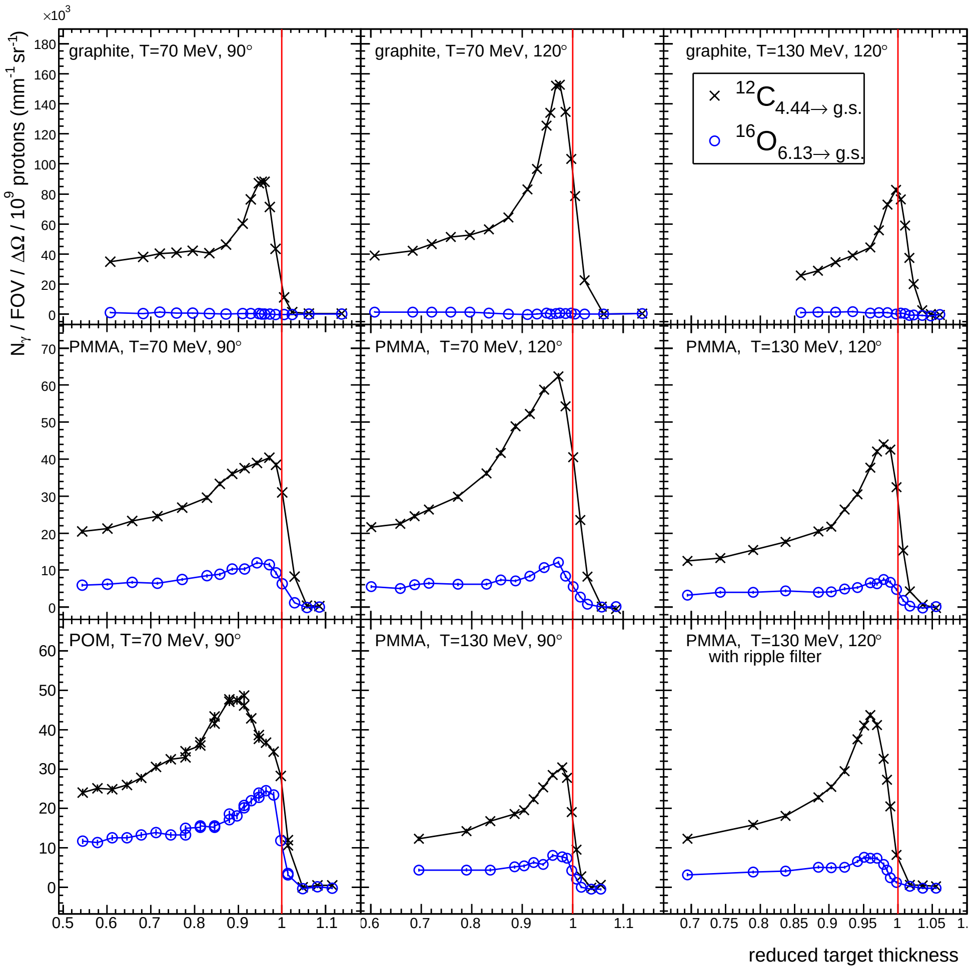
Depth Profile

PMMA target, 70 MeV beam energy, 120° observation angle



- Vertical red line: Proton range in PMMA for 70 MeV beam energy
- Steep slope behind maximum gamma yield in both cases!

Overview of Experimental Data Test Beam HIT 2015



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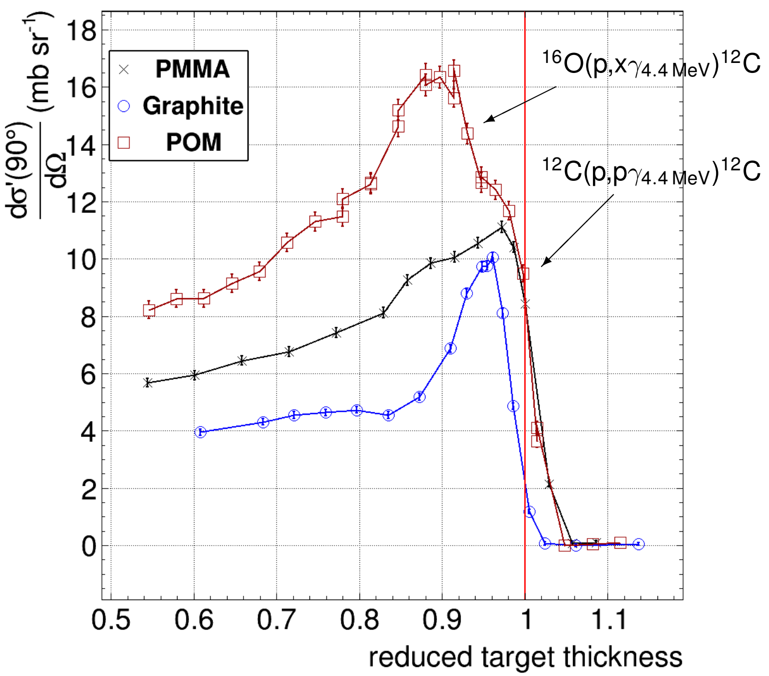
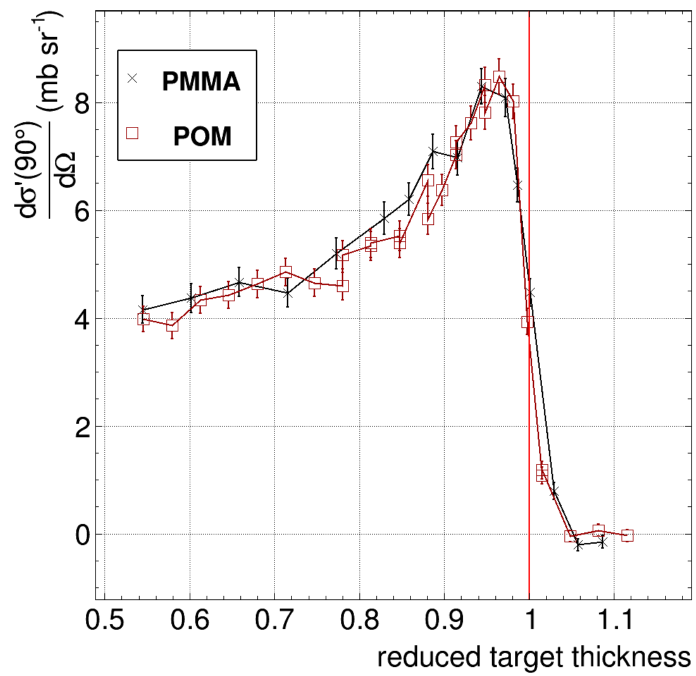
Dependence on Chemical Composition

70 MeV beam energy, 90° detection angle

$^{12}C_{4.44 \rightarrow g.s.}$

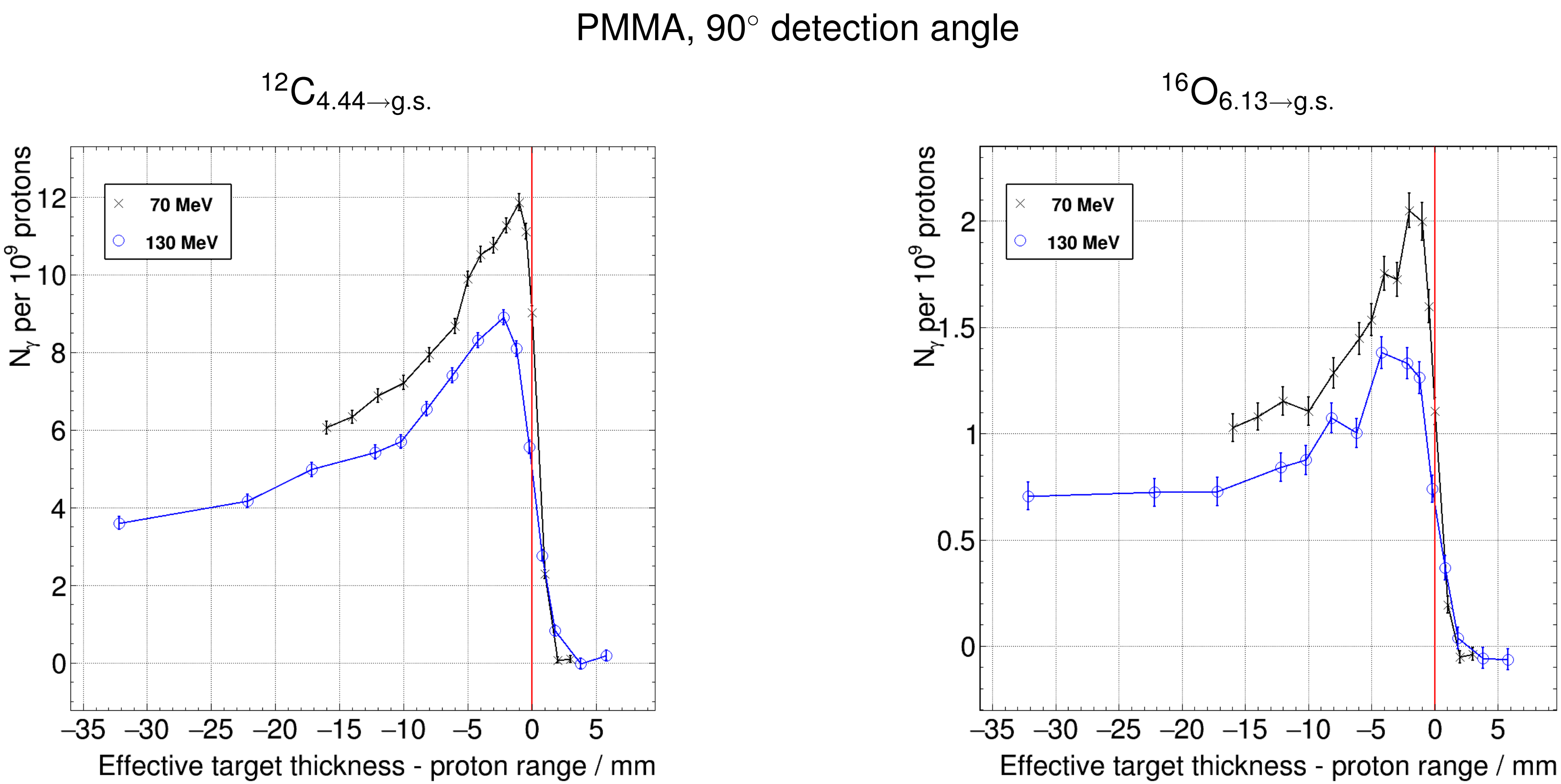


$^{16}O_{6.13 \rightarrow g.s.}$



Material	Chemical composition	Density / g cm^{-3}
PMMA	$(C_5O_2H_8)_n$	1.19
Graphite	C	1.74
POM	$(CH_2O)_n$	1.43

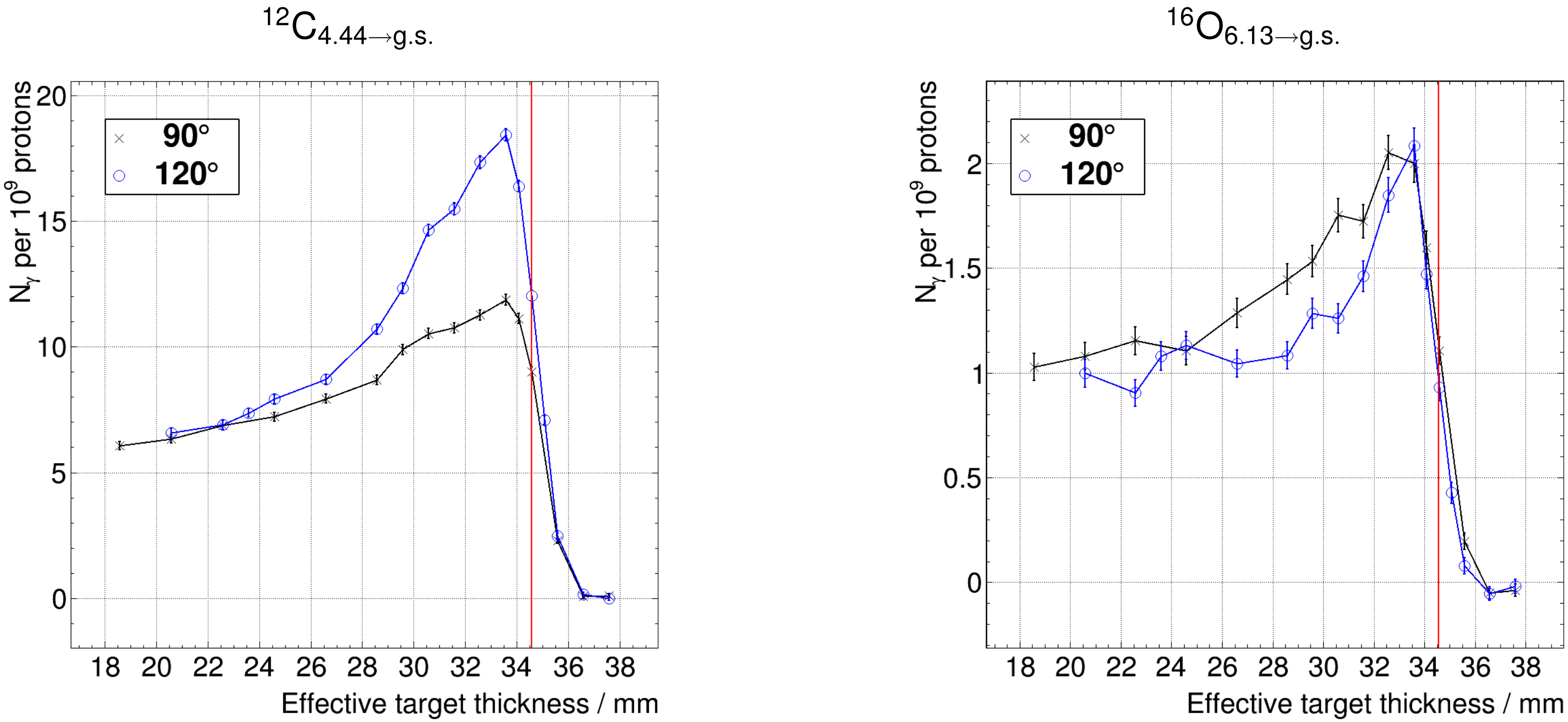
Dependence on Beam Energy



- Reduced integral because of elimination of protons from the beam
- Broadening of the profile because of stochastic energy loss

Dependence on Detection Angle θ

PMMA, 70 MeV beam energy



- Single-slit- and Compton camera observe multiple angles at once!
- $\theta \neq 90^\circ \Rightarrow$ complex reconstrution algorithms and a decrease in spatial resolution

Conclusion and Outlook

- Achieved:
  - Successful measurement of the depth profiles for $^{12}C_{4.44\rightarrow g.s.}$- and $^{16}O_{6.13\rightarrow g.s.}$-lines
  - Steep slope behind maximum gamma yield seen for all studied reactions and measurement conditions
  - Strong influence of phantom composition on $^{12}C_{4.44\rightarrow g.s.}$ peak shape
  - Depth profile characteristics at increasing beam energy studied
  - Influence of detection angle on depth profile studied

- Outlook / ongoing:
  - Publish paper about results (currently in peer review by Phys. Med. Biol.)
  - Upgrade setup and go for next beam time
  - Derive conclusions and start with setup of a gamma/Compton camera

Thank you for your attention!

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UNIWERSYTET ŚLĄSKI W KATOWICACH

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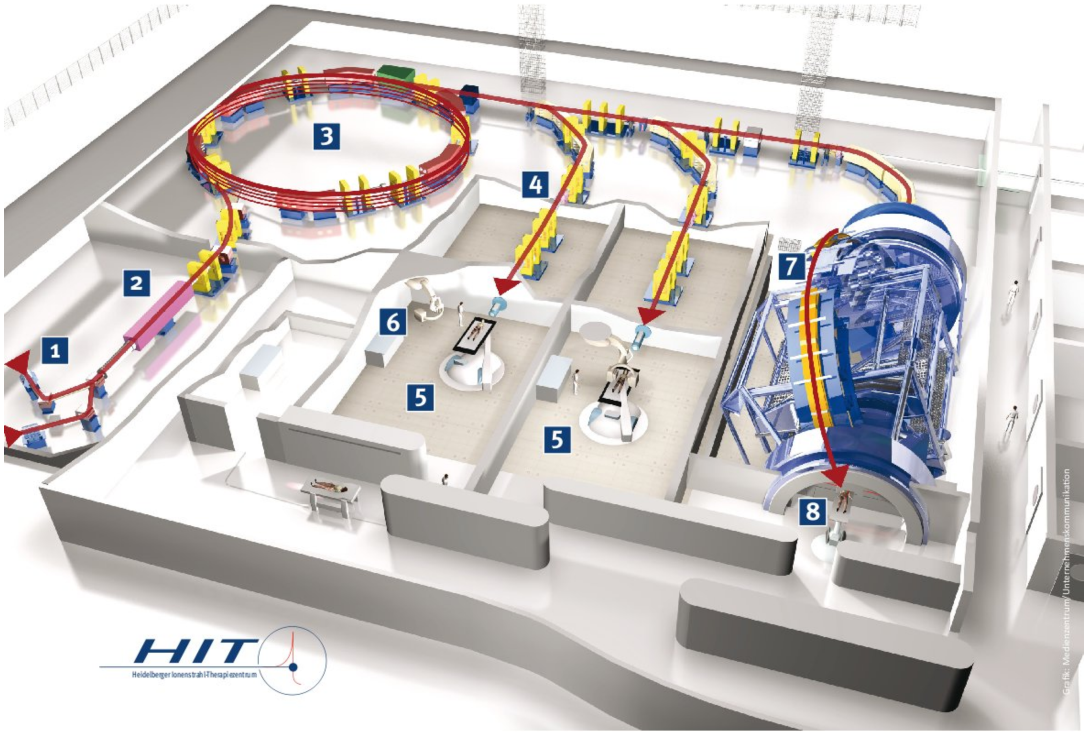
The project „Investigation of gamma emission in experimental modeling of hadron therapy” is carried out within the POMOST programme of the Foundation for Polish Science, co-financed from the European Union under the European Regional Development Fund.

Backup

Heidelberger Ionenstrahl-Therapiezentrum (HIT)

Proton beam parameters:

Energy range	Maximum intensity	FWHM	
		70 MeV	130 MeV
48 - 221 MeV	3.2×10^9 p$^+$/second	22.8 mm	12.5 mm



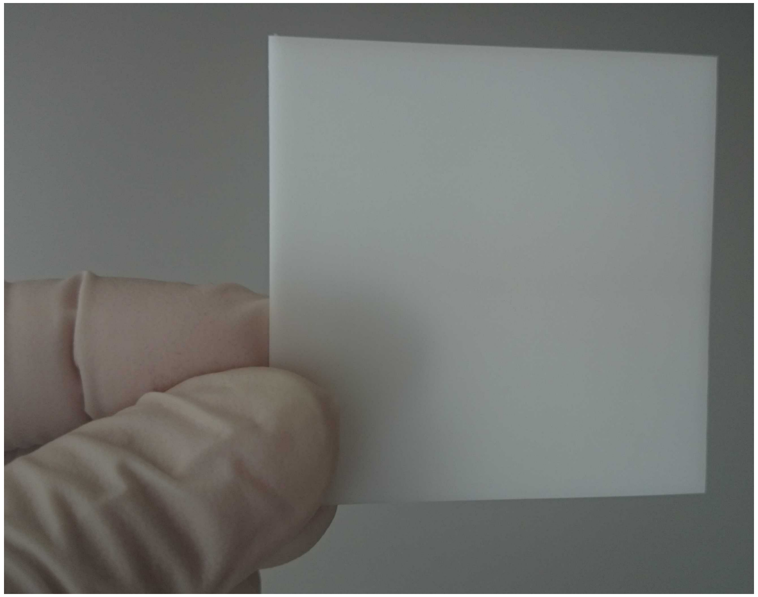
1 Ion sources
2 Linear accelerator
3 Synchrotron
4 Beam guidance towards treatment rooms
5 Treatment rooms with static beam nozzle
6 Patient position control system
7 Combined ion gantry
8 Treatment room in ion gantry

Heidelberger Ionenstrahl-Therapiezentrum. `https://www.klinikum.uni-heidelberg.de/Accelerator-facility.117968.0.html?&L=1`

Target Material

Material	Chemical composition	Density / g cm^{-3}	Slice thickness / mm
PMMA	$(C_5O_2H_8)_n$	1.19	2
POM	$(CH_2O)_n$	1.43	1
Graphite	C	1.74	1

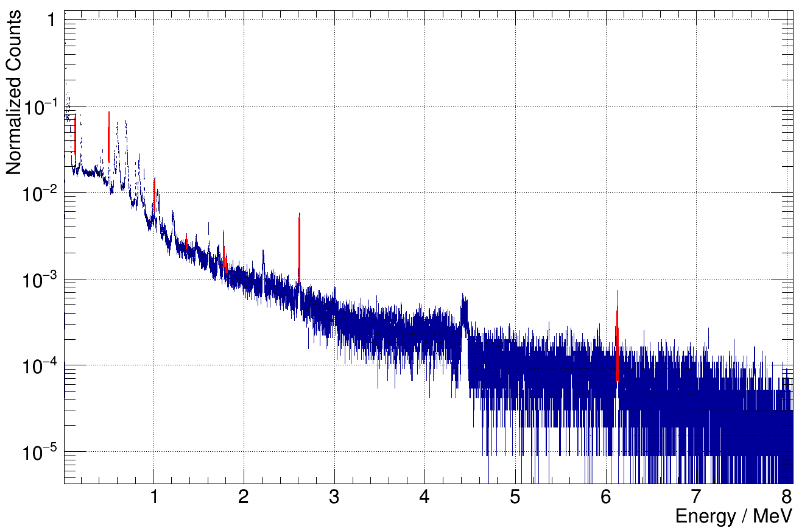
POM target wedges

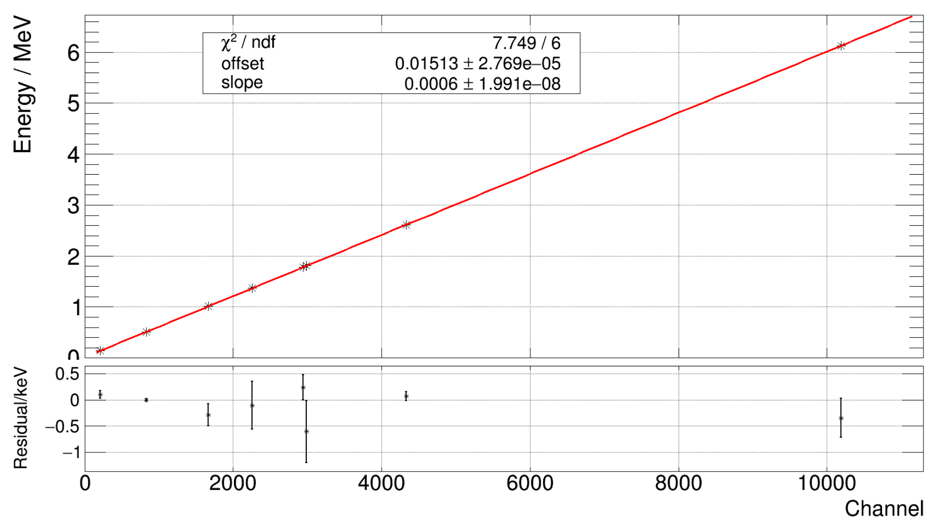


POM thin target slice

Normalization and Calibration of Gamma Spectra

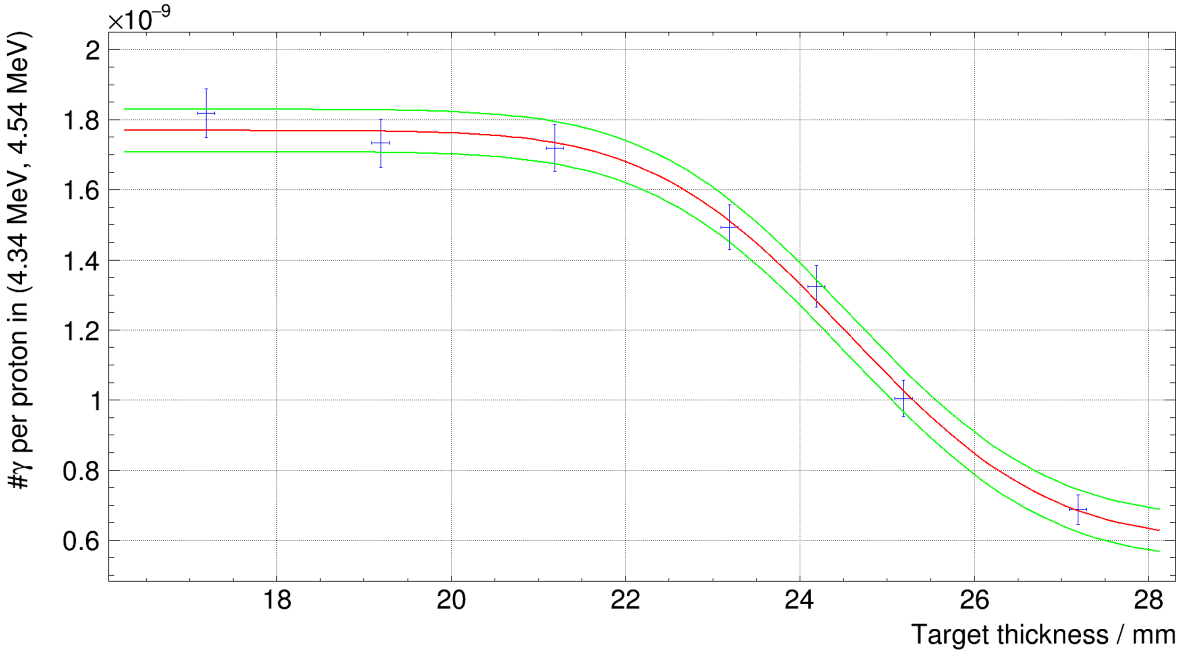
- Normalization: Use Beam Current Monitors and HIT calibration files
  $\rightarrow$ Normalization to number of protons in beam
- Calibration:
  - Pre-calibration using 4 caracteristic peaks in a single run (Anna Chrobak, Katowice)
  - Identification of reaction peaks in spectrum (mainly Daniel Böckenhoff Master's thesis)
  - Calibration performed for each run separately using 8 characteristic peaks
    $\rightarrow$ Systematical shifts of 6.1 MeV peak position below 5 keV over whole beam time





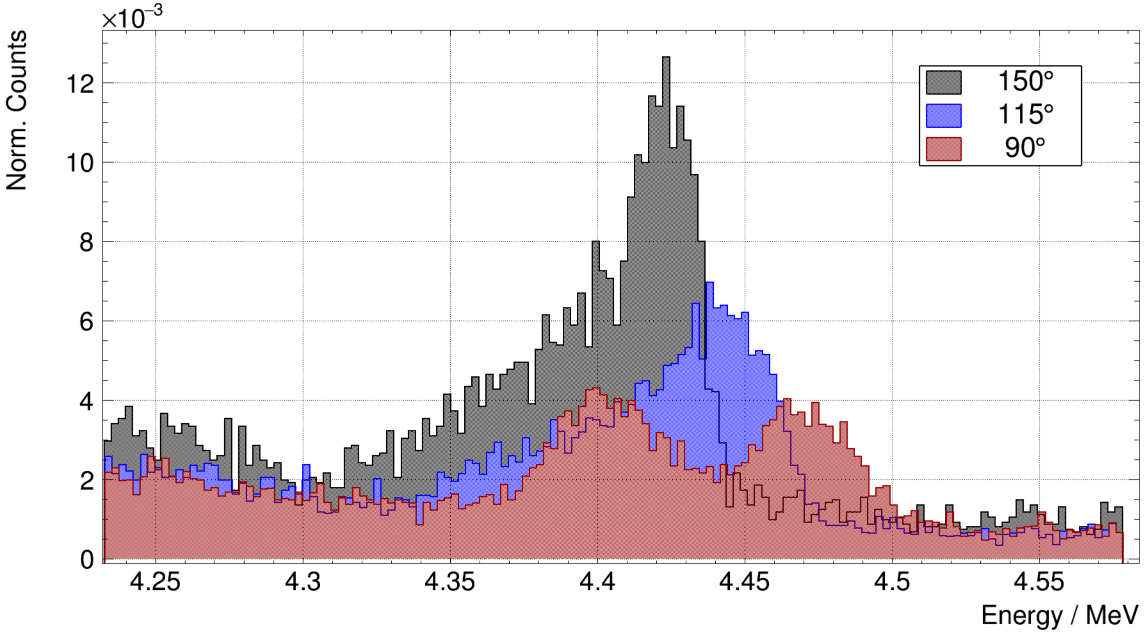
Background Parametrization

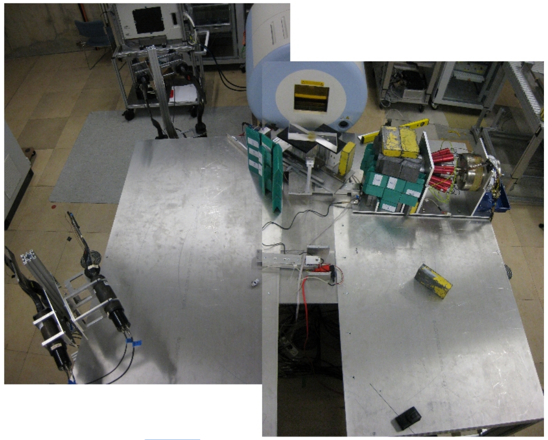
- Background is measured at different target thicknesses $\Rightarrow$ parametrization needed
- Automatized fit of error function implemented
- $f(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-\tau^2} d\tau$

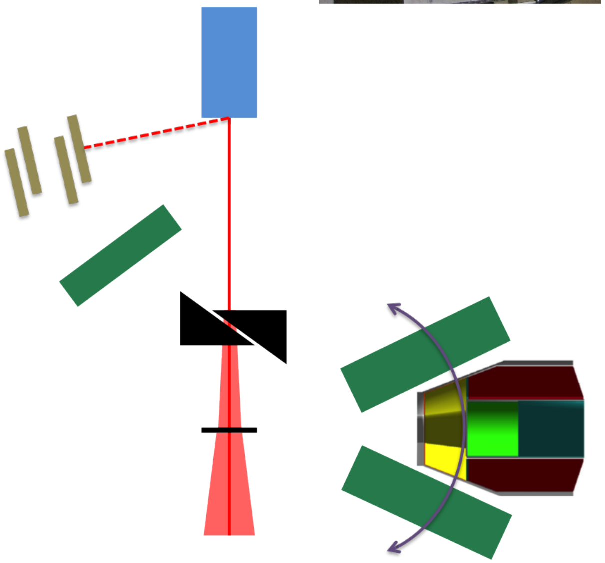


Background for 4.4 MeV peak of Graphite, 70 MeV beam energy, 120° observation angle

Investigation on angular effects





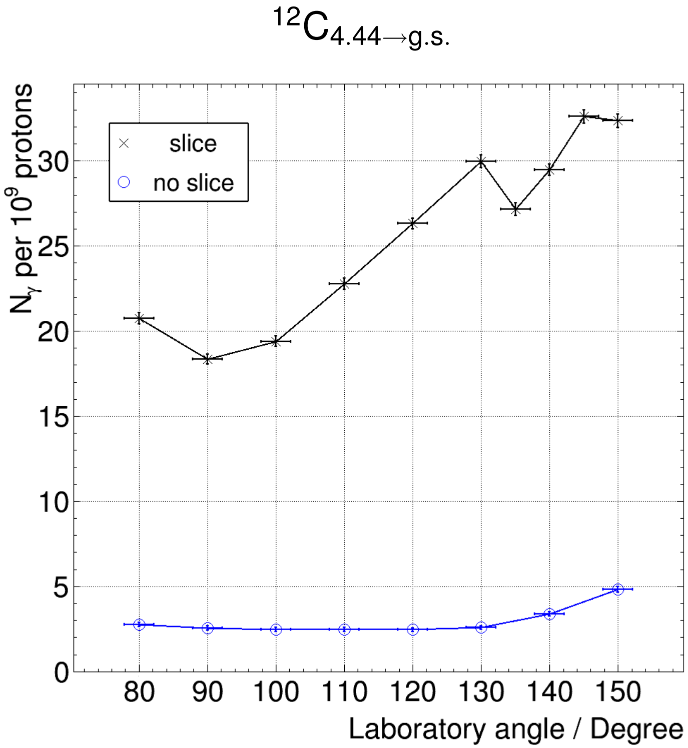


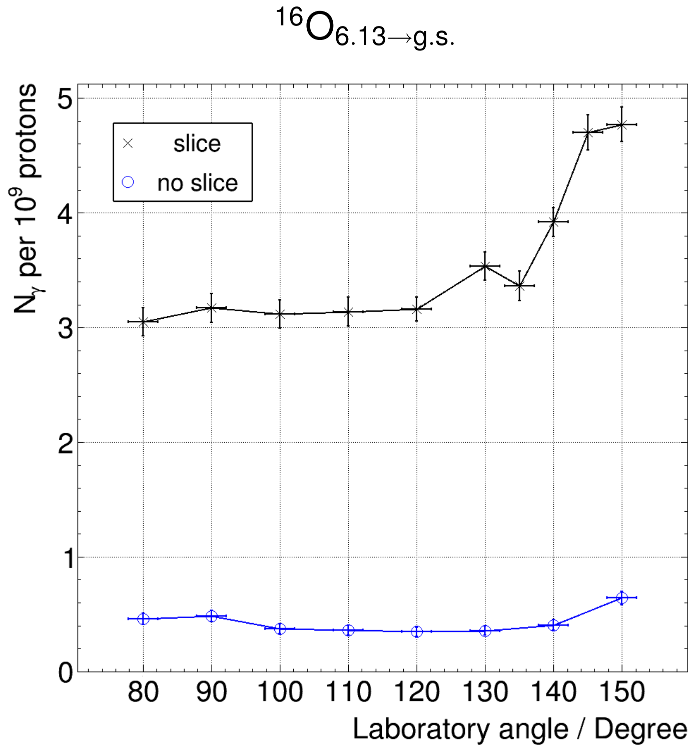
Angular dependence of

- peak integral (angular distribution)
- peak shape (coherent Doppler effect: 4.4-gamma emitted by carbon atom in-flight after collision with proton)

Angular Distribution

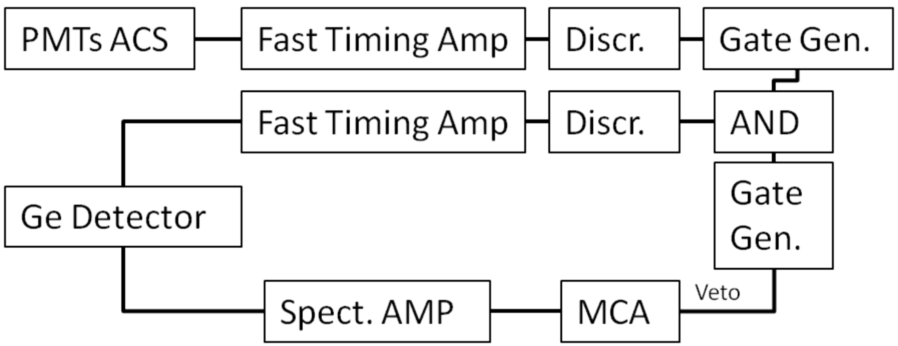
PMMA, 70 MeV beam energy

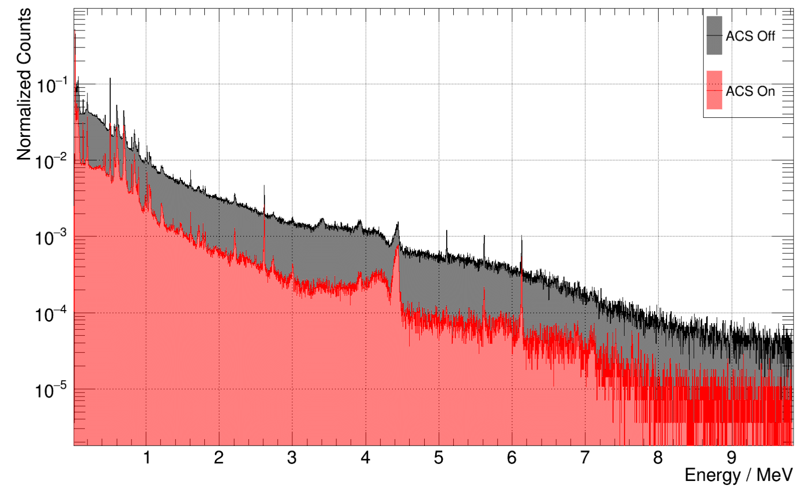




$\Rightarrow$ Backward detection angles give higher gamma output!

Performance of Active Compton-Shield





	Peak	Compton Cont.
Ranges	4.34-4.47 MeV	3.34-4.34 MeV
Reduction factor	$16.2 \pm 2.5\,\%$	$73.3 \pm 0.5\,\%$
Ranges	6.12-6.14 MeV	5.12-6.12 MeV
Reduction factor	$23.4 \pm 7.7\,\%$	$75.7 \pm 1.4\,\%$