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

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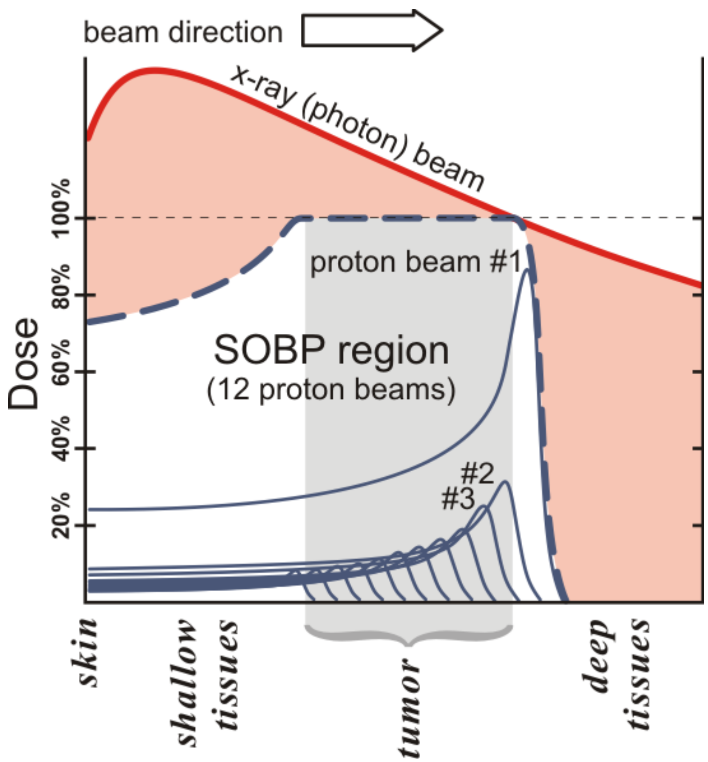
Contents

Introduction to Ion Therapy

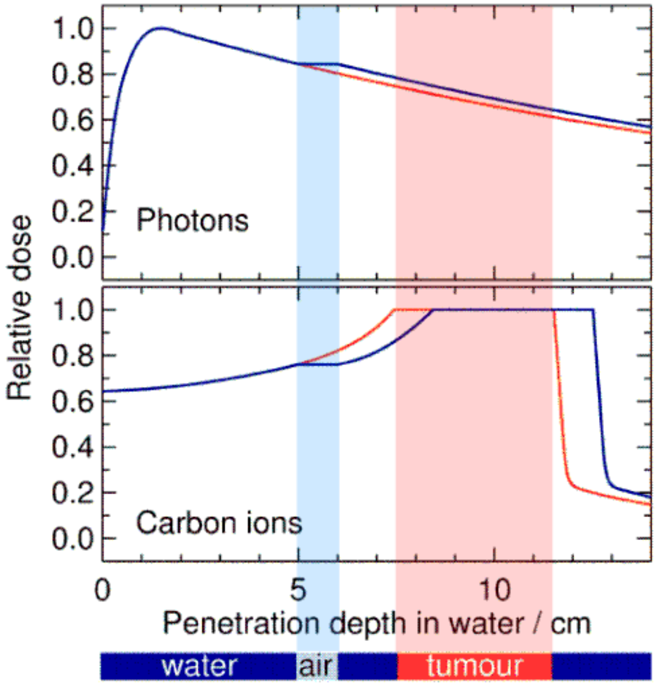
- Radiation therapy is one important method to treat malignant tumors
- Advantages of ion therapy comparing to x-rays:
  - Biological effectiveness: Double-strand breaks (heavy ions only)
  - Physical: Dose distribution (all ions)



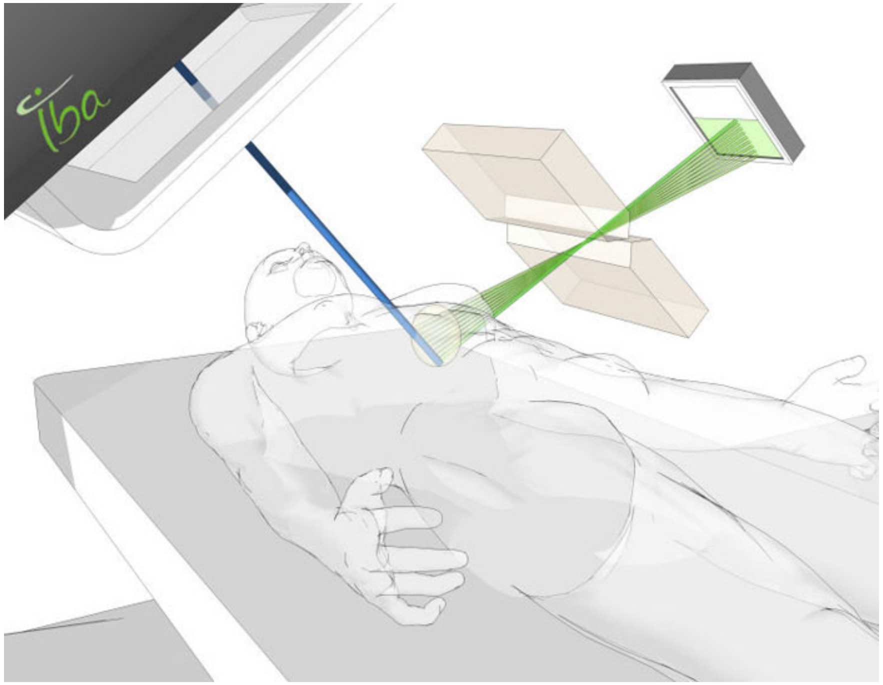
Dose distribution of different radiation typesLevin et al (2005): "Proton beam therapy". In: British Journal of Cancer.

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

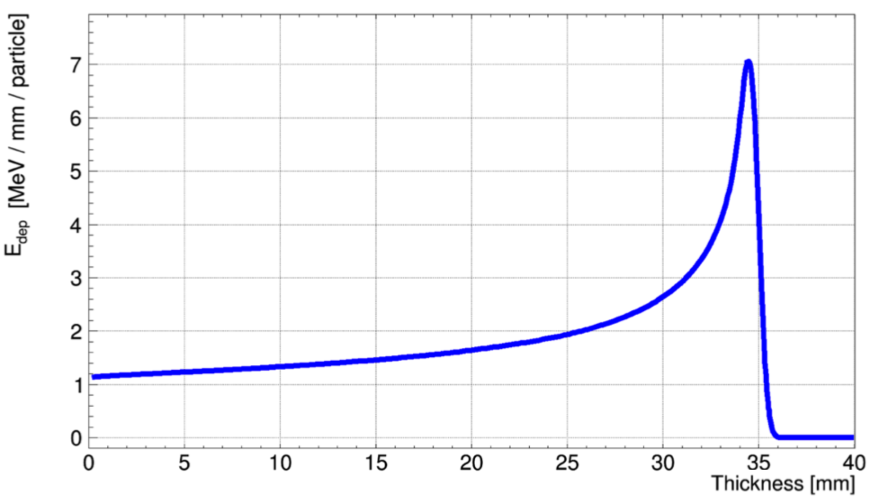


Prompt gammas emitted during ion therapy used for online beam monitoring
http://medicalphysicsweb.org/cws/article/research/49909

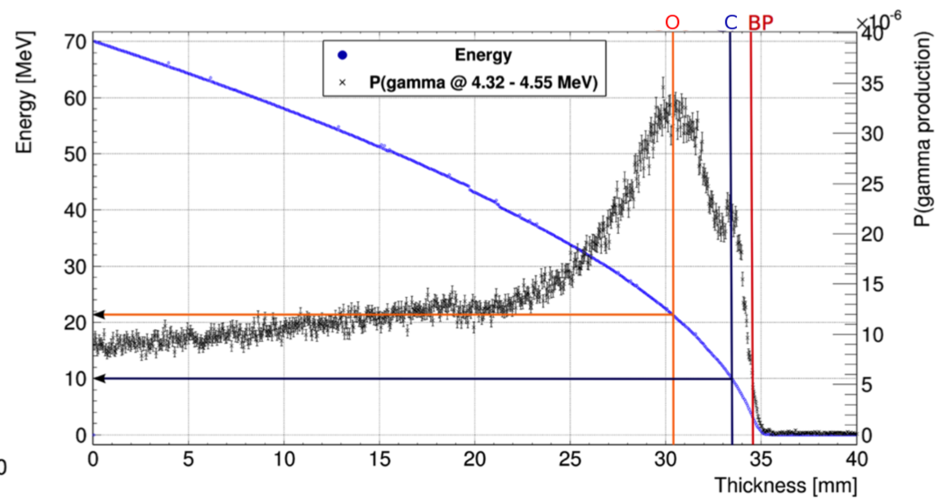
Introduction to Prompt Gammas

- 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
- Promising lines: $^{12}C_{4.44 \rightarrow g.s.}$ and $^{16}O_{6.13 \rightarrow g.s.}$

Bragg Peak

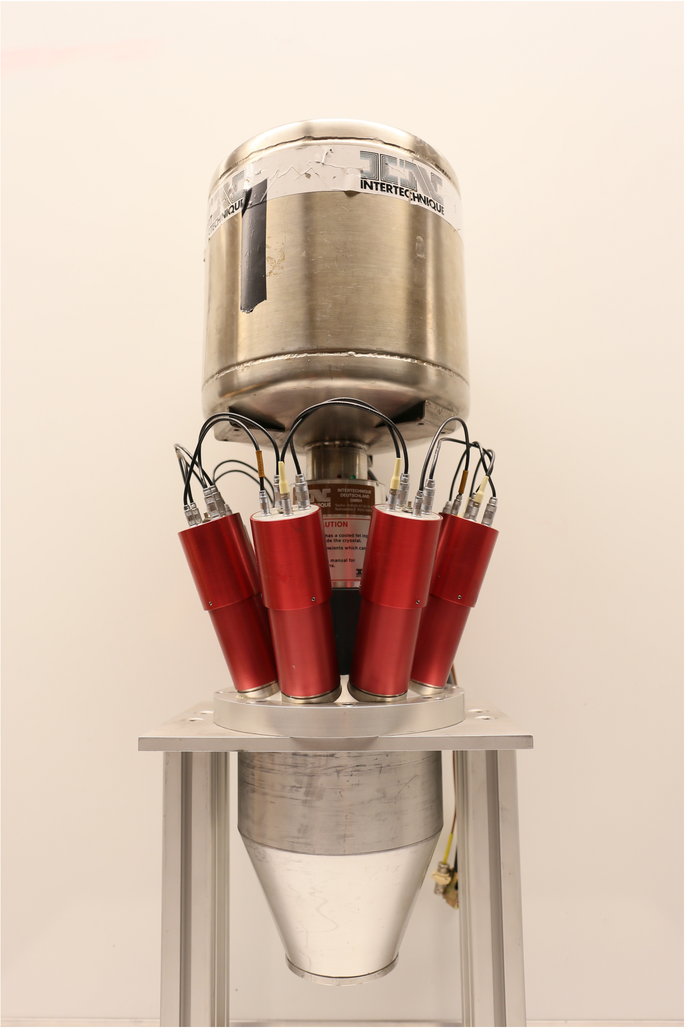


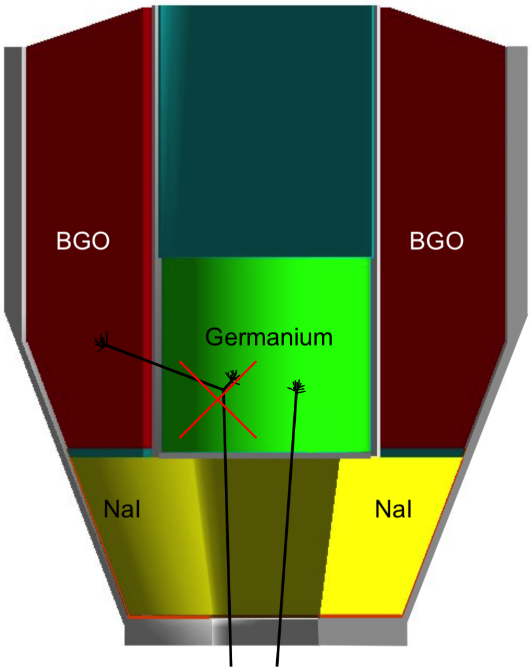
Mean proton energy and prompt gamma emission



GEANT4 Simulation of proton Bragg Peak and corresponding prompt gamma emission in PMMA (Sabine Feyen)

HPGe Detector with Active Compton-Shield

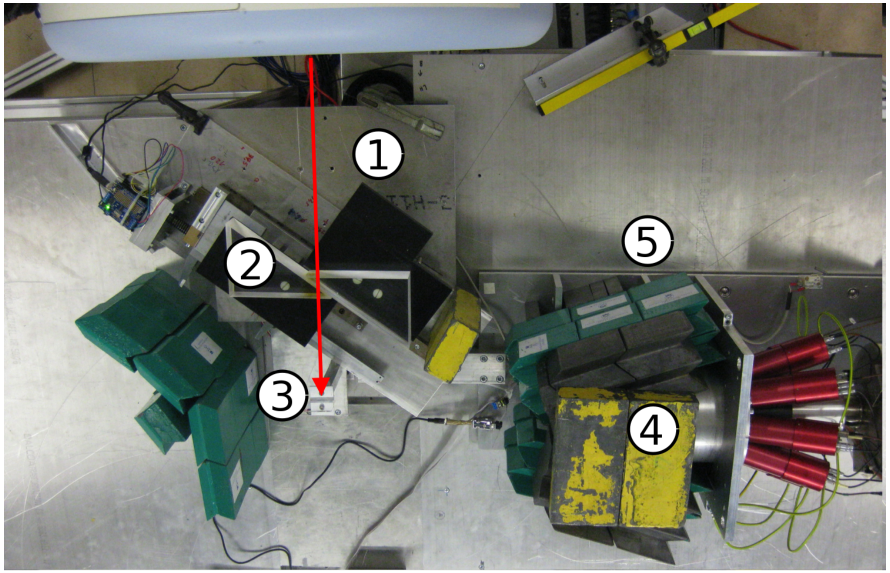


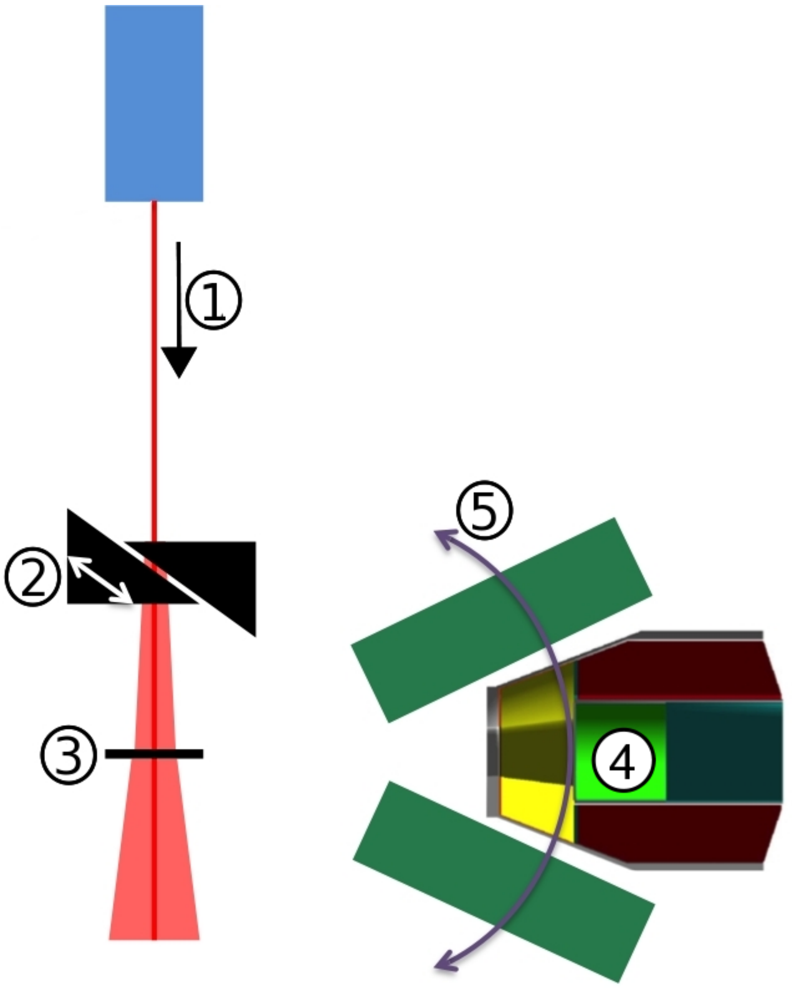


High-Purity Germanium Detector:

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

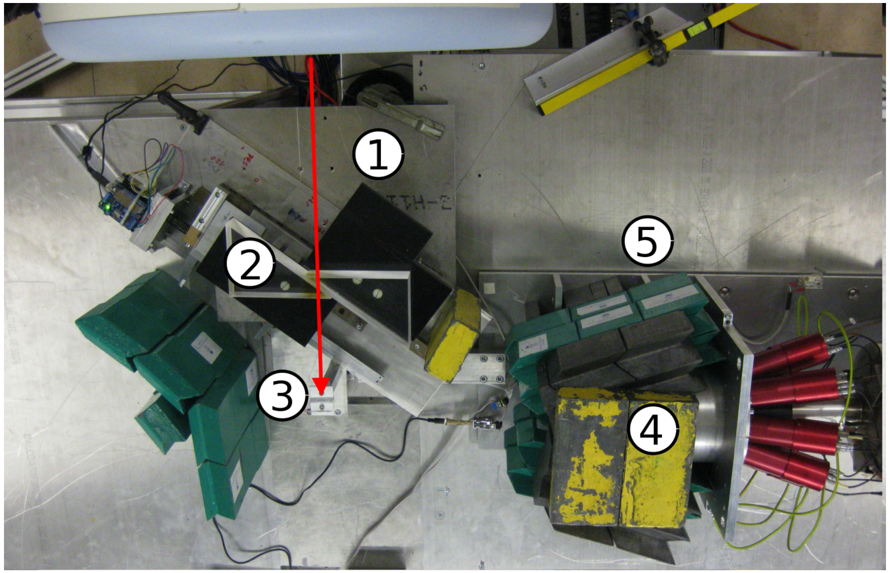
Setup during Test Beam at HIT 2015

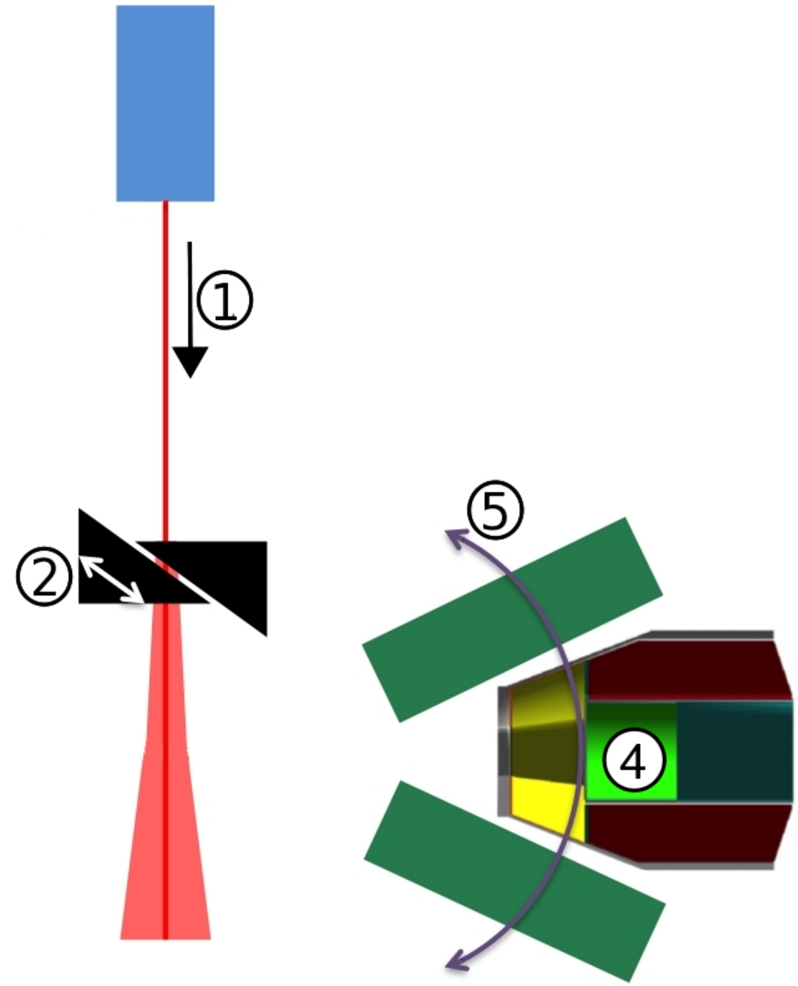




1 Proton pencil beam (70 and 130 MeV)
2 Adjustable target thickness (**wedges**)
3 Thin target **slice**
4 HPGe detector to measure prompt gamma radiation from thin slice
5 Detector rotation system

Setup during Test Beam at HIT 2015





1 Proton pencil beam (70 and 130 MeV)

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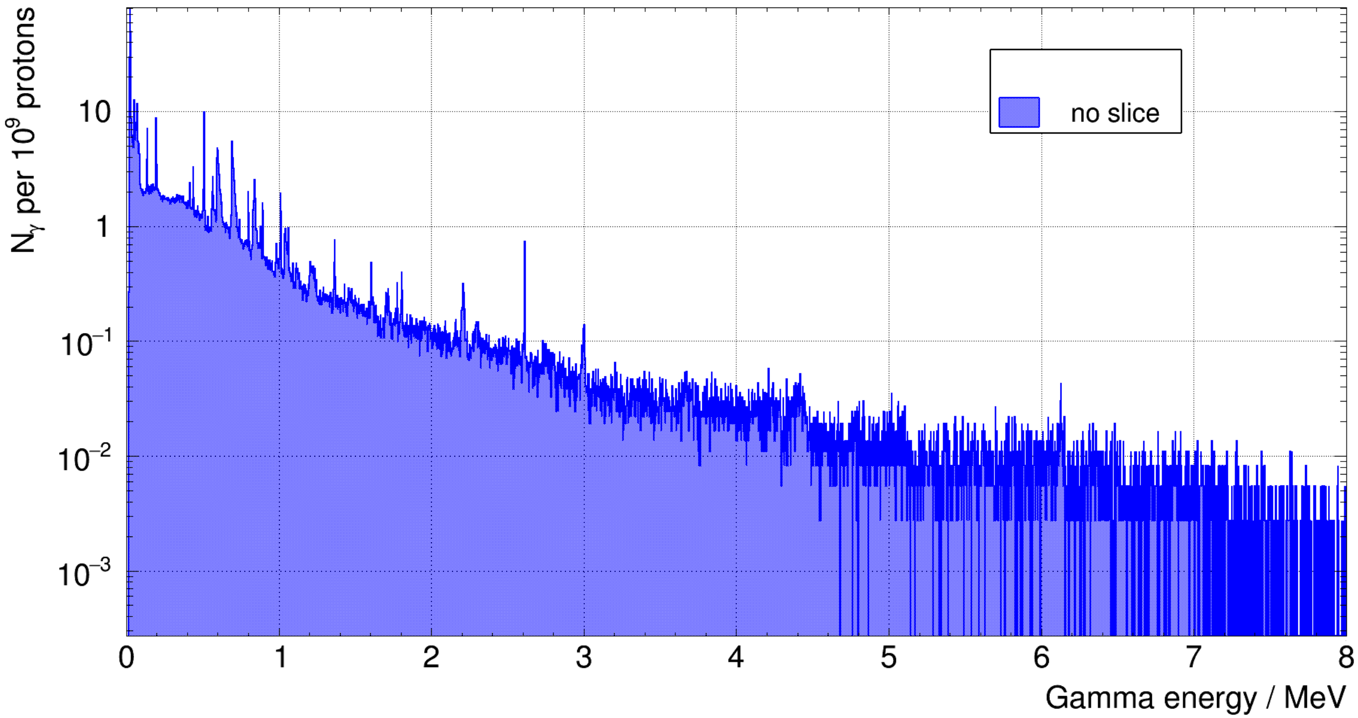
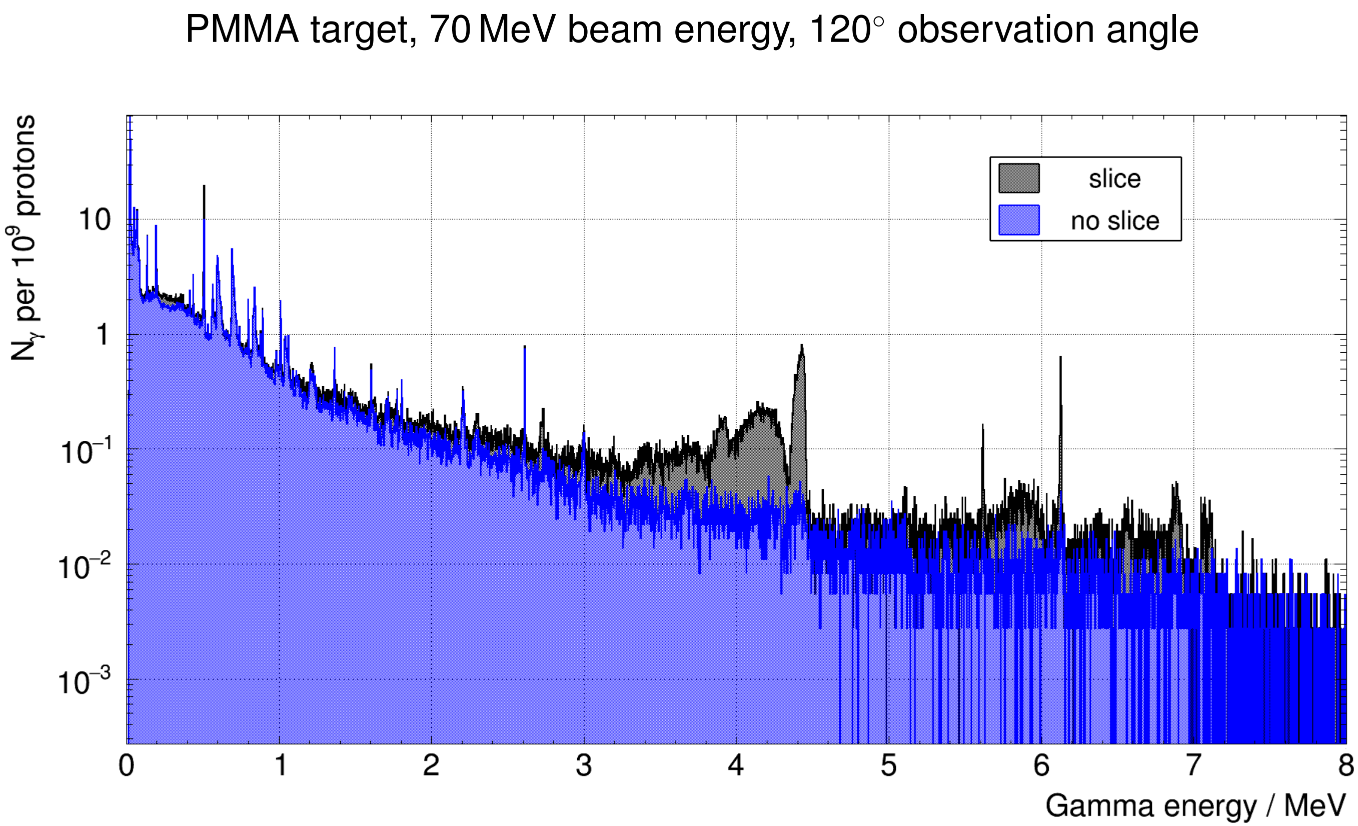
Gamma Spectrum

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



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

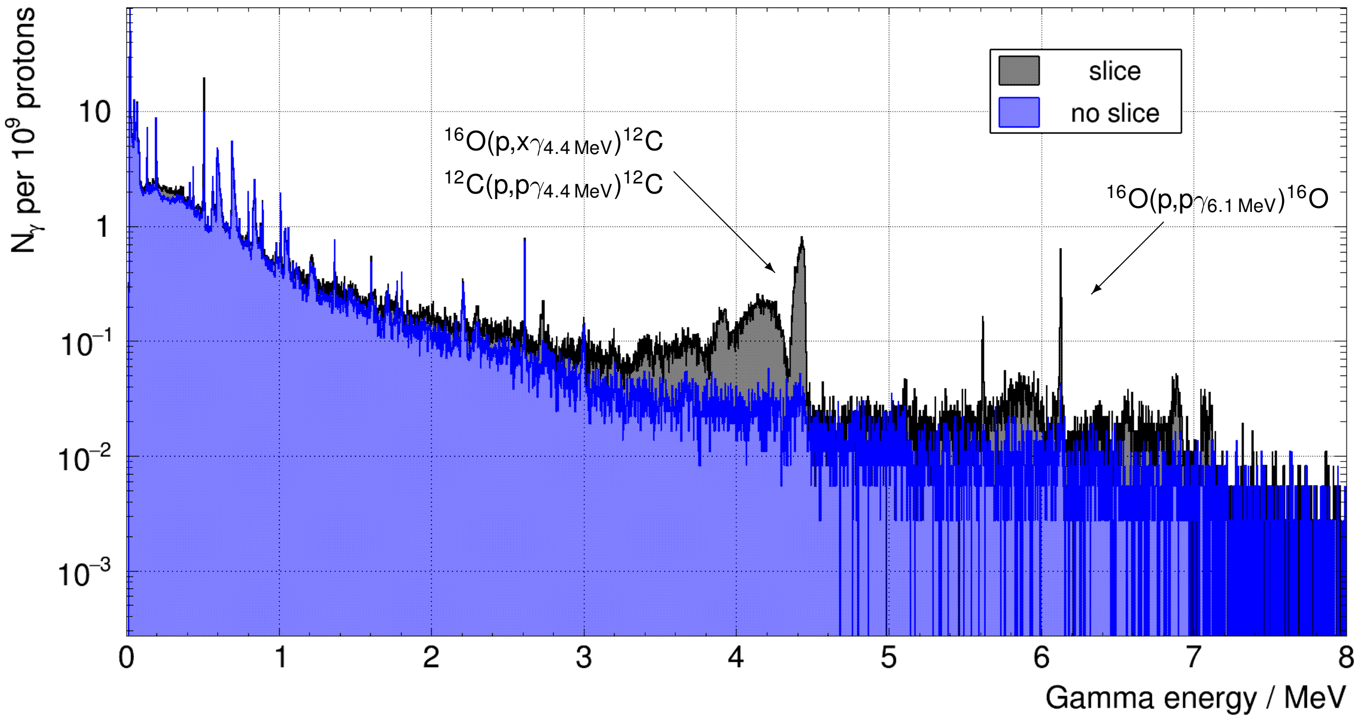
Gamma Spectrum



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

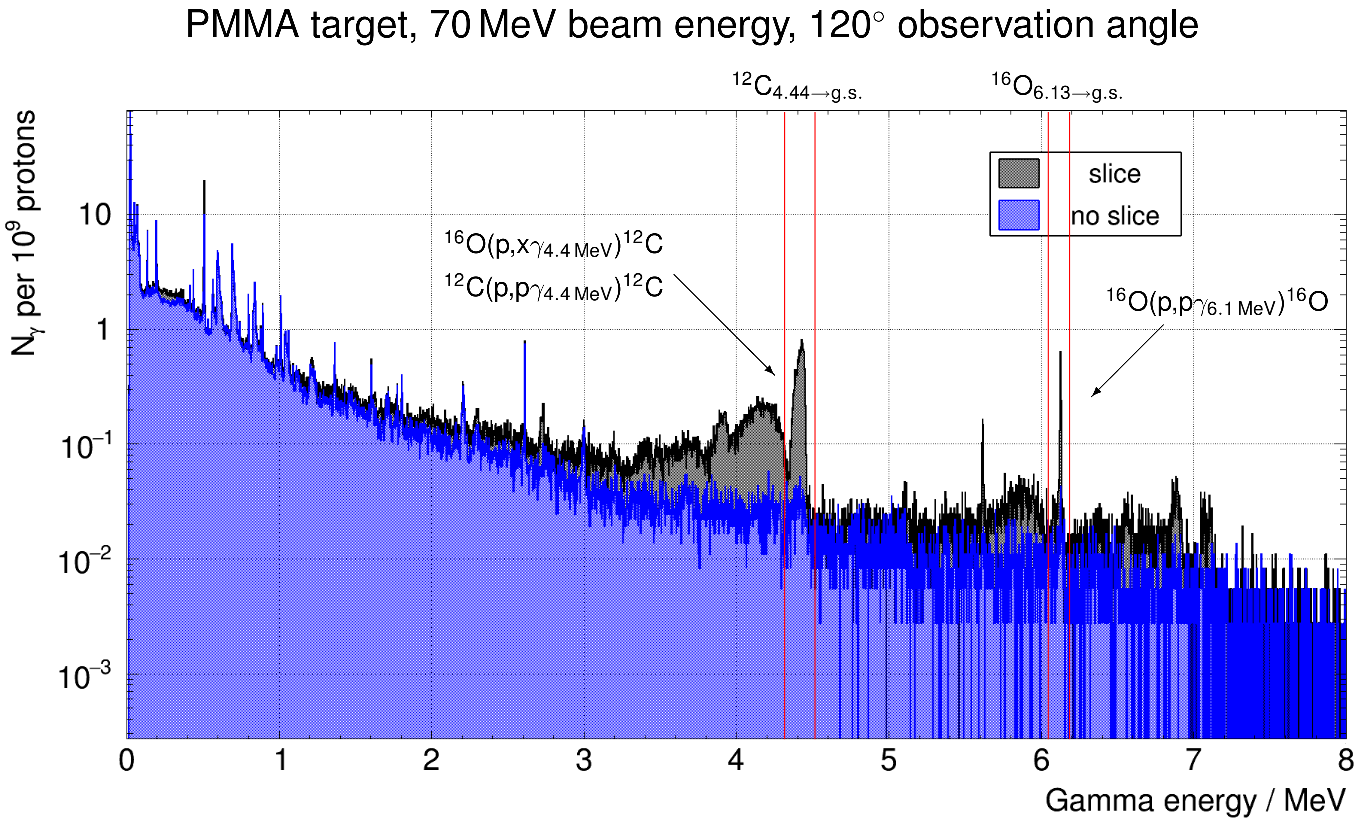
Gamma Spectrum

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



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

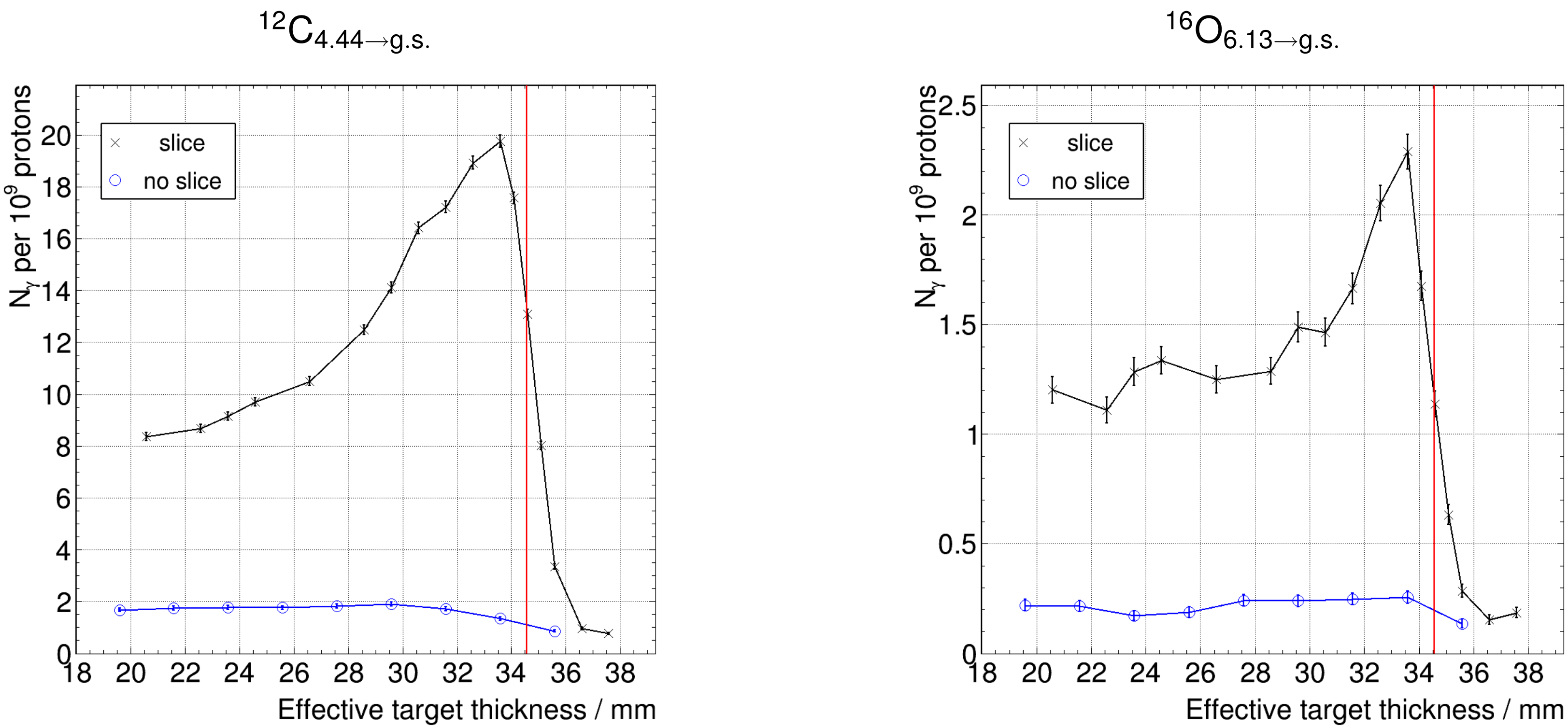
Gamma Spectrum



- 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!

Parameter Overview Test Beam HIT 2015

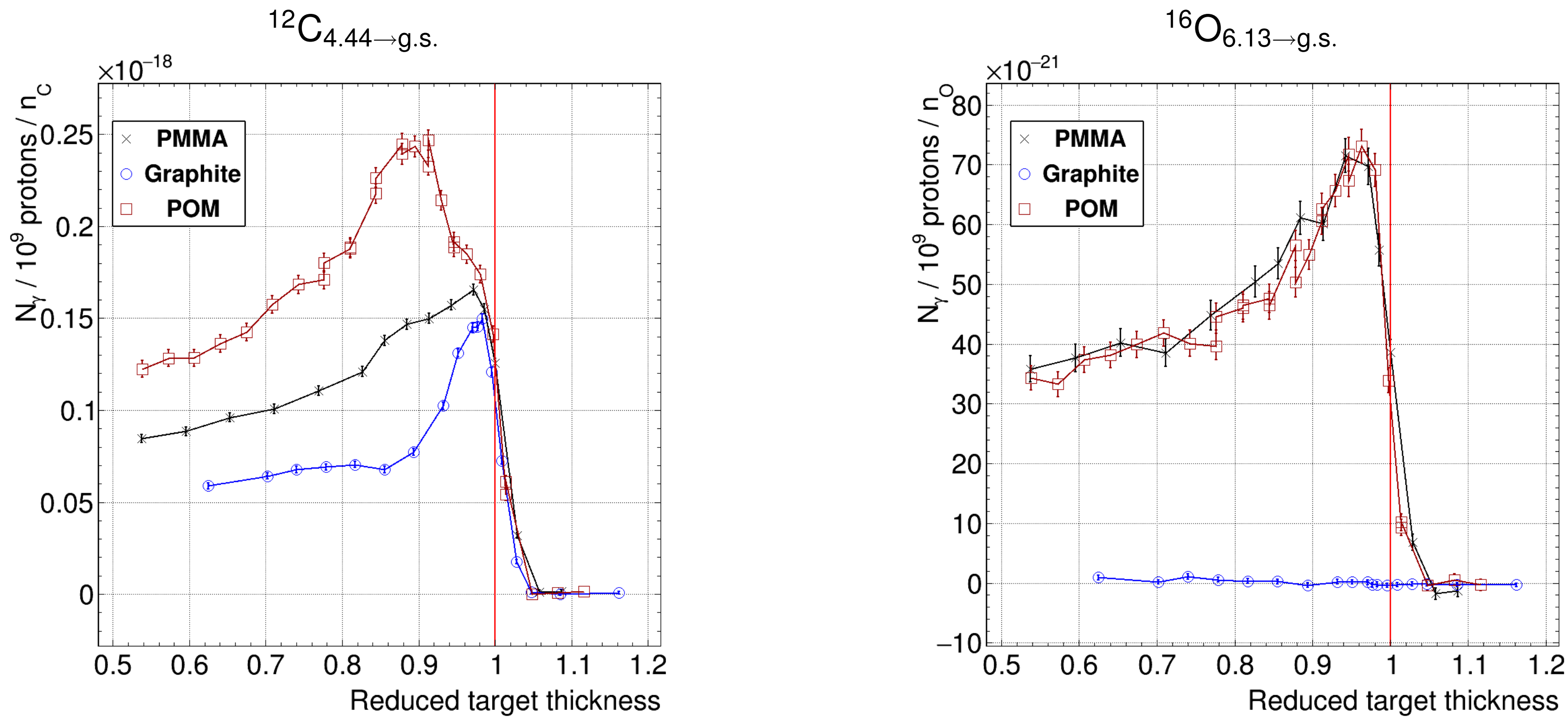
Varied measurement parameters:

- Target material
- Beam energy
- Observation angle

Material	Energy / MeV	Angle	Comment
PMMA	70	90°	
	70	120°	
	130	90°	
	130	120°	
	130	120°	With Ripple Filter
	70	80° - 150°	Angular distribution
Graphite	70	90°	
	70	120°	
	130	120°	
	70	80° - 150°	Angular distribution
	88.33	90° - 150°	Angular distribution
POM	70	90°	

Dependence on Target Material

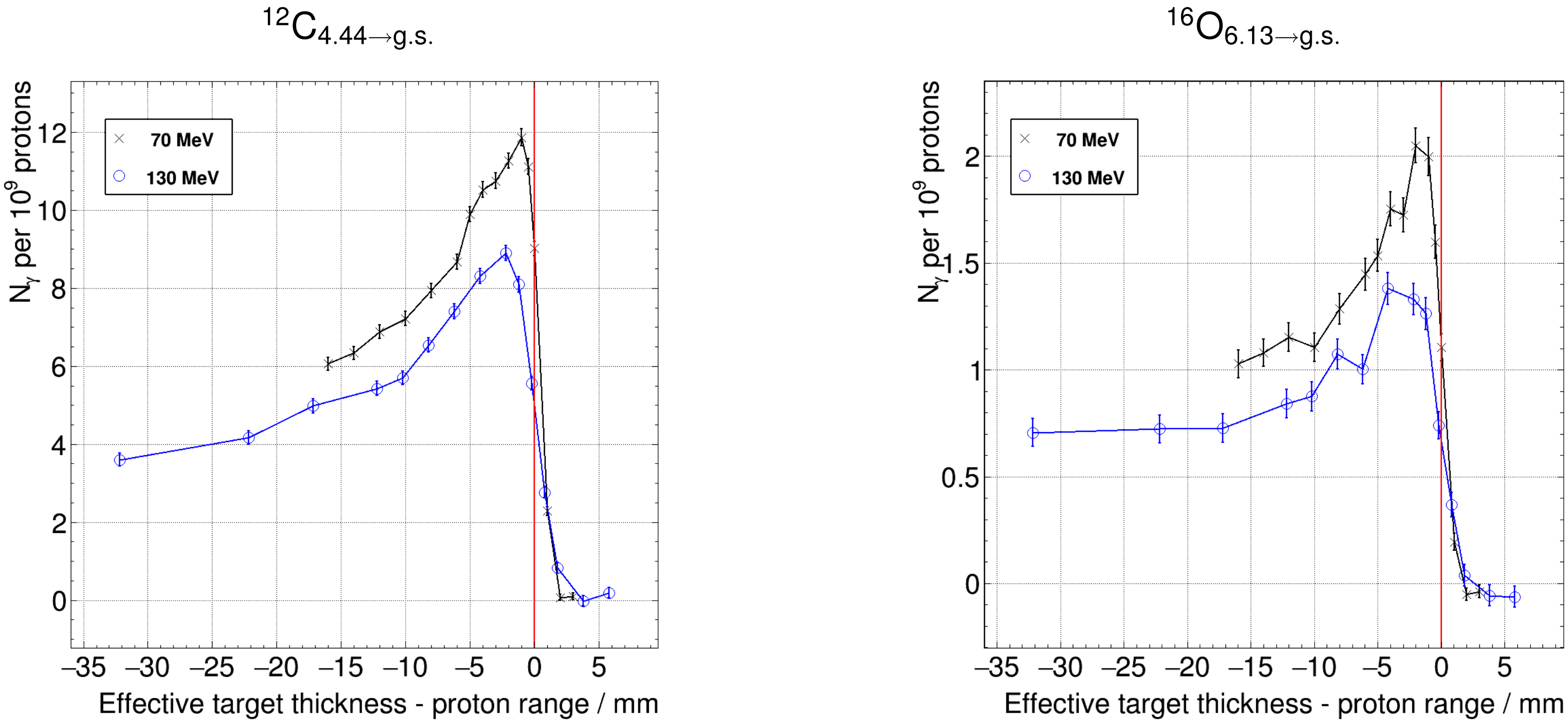
70 MeV beam energy, 90° observation angle



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

PMMA, 90° observation angle

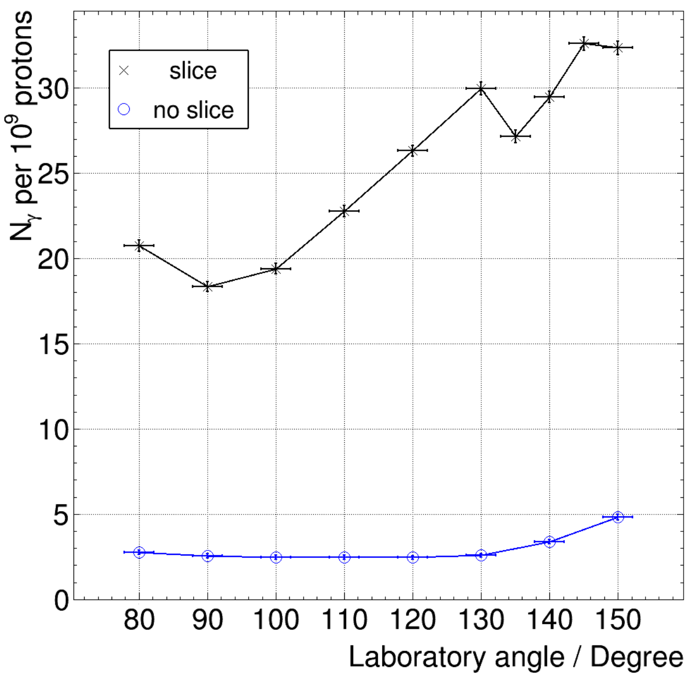


- Reduced integral because of elimination of protons from the beam
- Broadening of the profile because of stochastic energy loss

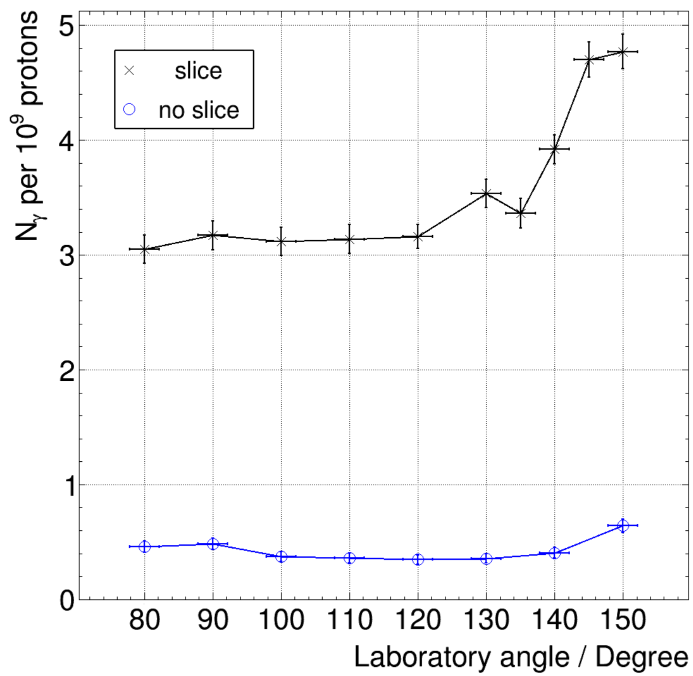
Angular Distribution

PMMA, 70 MeV beam energy

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

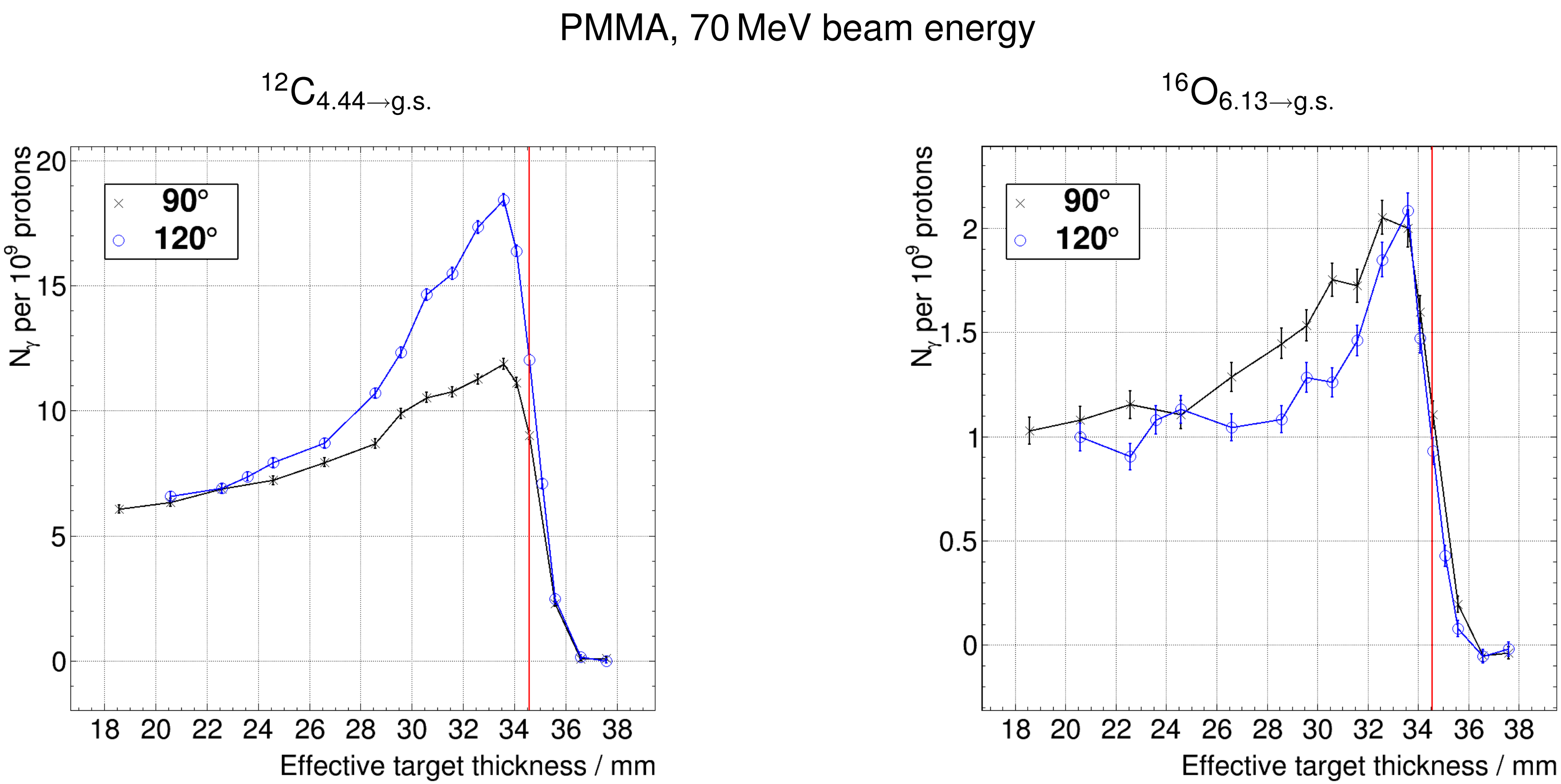


$^{16}O_{6.13 \to g.s.}$



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

Angular Distribution: Depth Profile



- Single-slit- and Compton camera observe multiple angles at once!
- Deviations from 90° observation angle lead to 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
  - Angular distribution and influence on depth profile studied
- Outlook / ongoing:
  - Publish paper about results
  - Upgrade setup and go for next beam time
  - Derive conclusions and start with setup of a gamma/Compton camera

Thank you for your attention!

UNIWERSYTET JAGIELLOŃSKI W KRAKOWIE

UNIWERSYTET ŚLĄSKI W KATOWICACH

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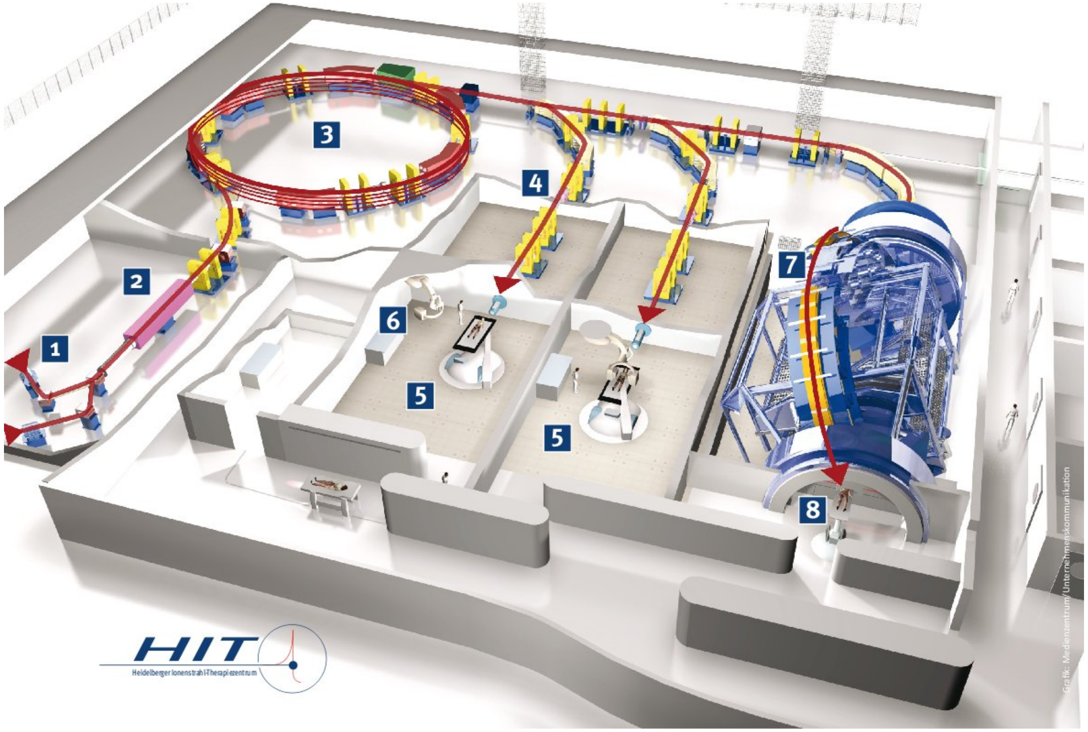
The project „Investigation of gamma emission in experimental modeling of hadron therapy" is carried out within the POMOST programme of the Foundation for Polish Science, co-financed from the European Union under the European Regional Development Fund.

Heidelberger Ionenstrahl-Therapiezentrum (HIT)

Proton beam parameters:

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



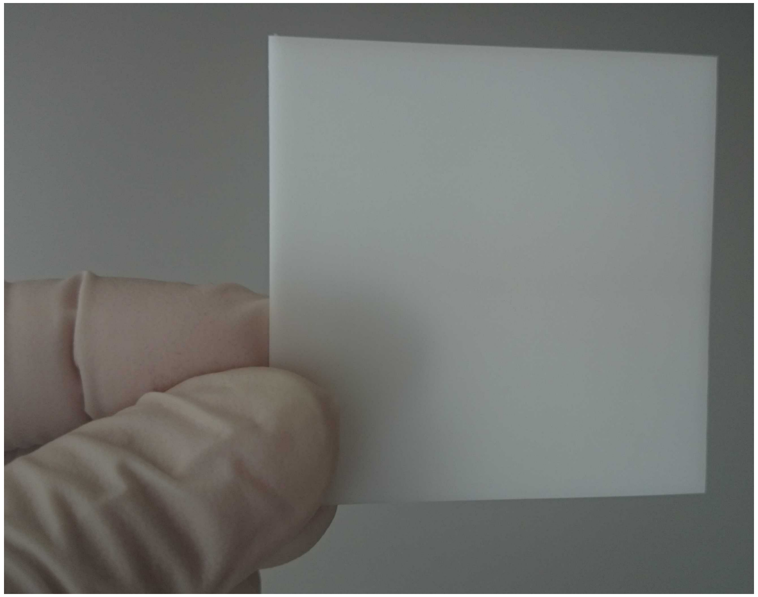
1 Ion sources
2 Linear accelerator
3 Synchrotron
4 Beam guidance towards treatment rooms
5 Treatment rooms with static beam nozzle
6 Patient position control system
7 Combined ion gantry
8 Treatment room in ion gantry

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

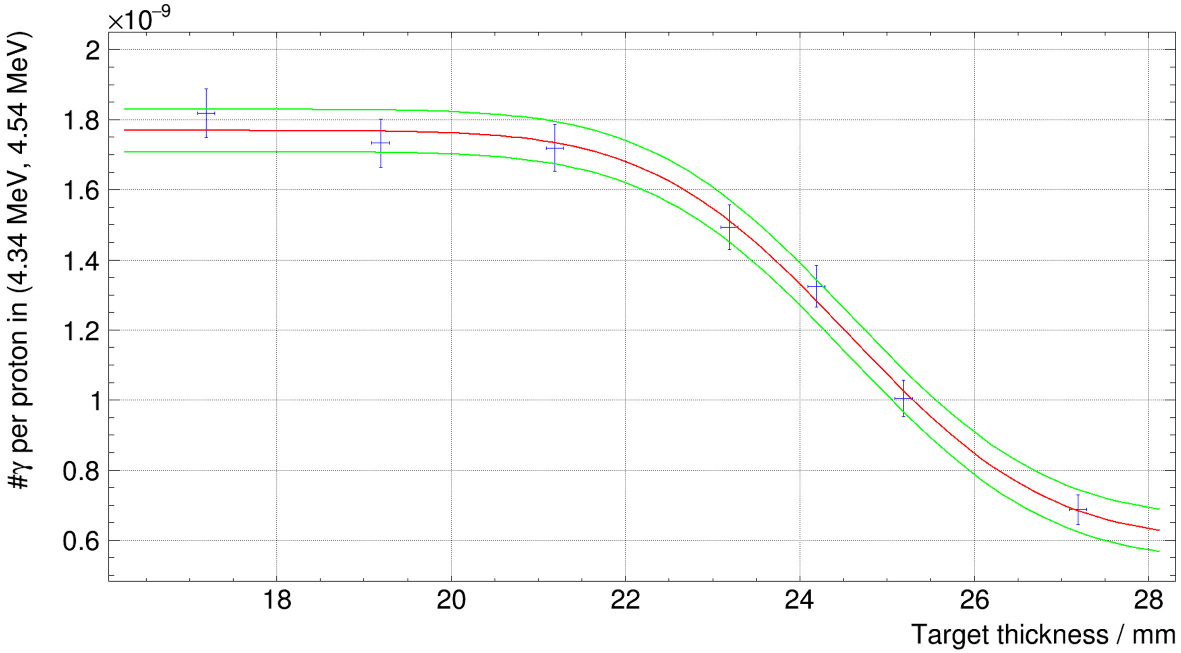
POM target wedges



POM thin target slice

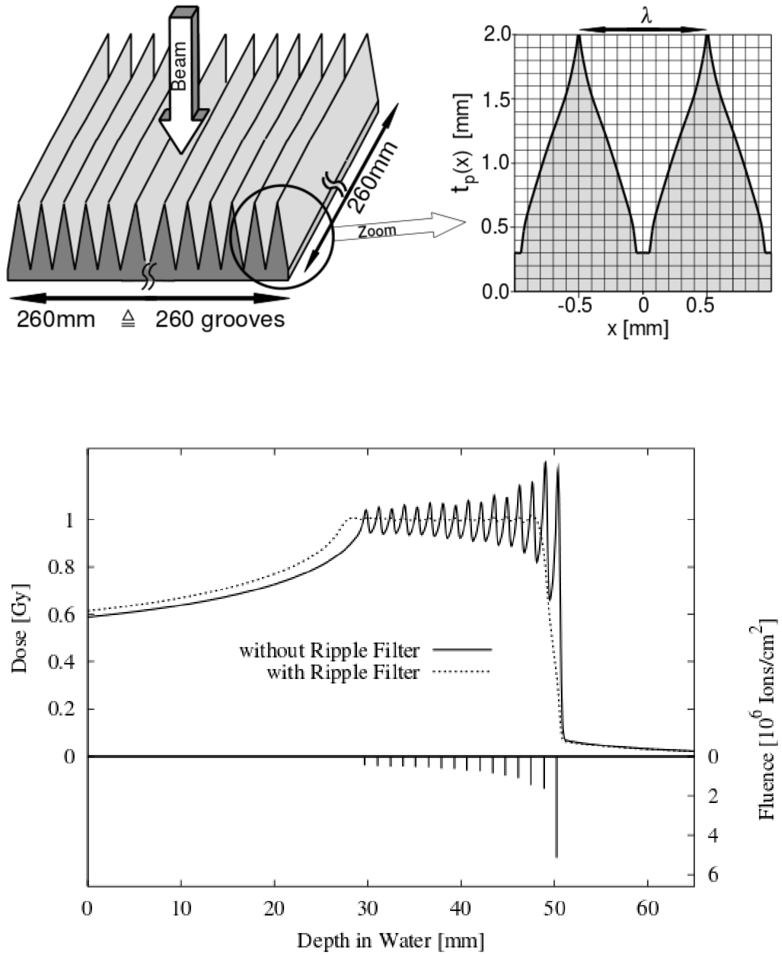
Background Parametrization

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



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

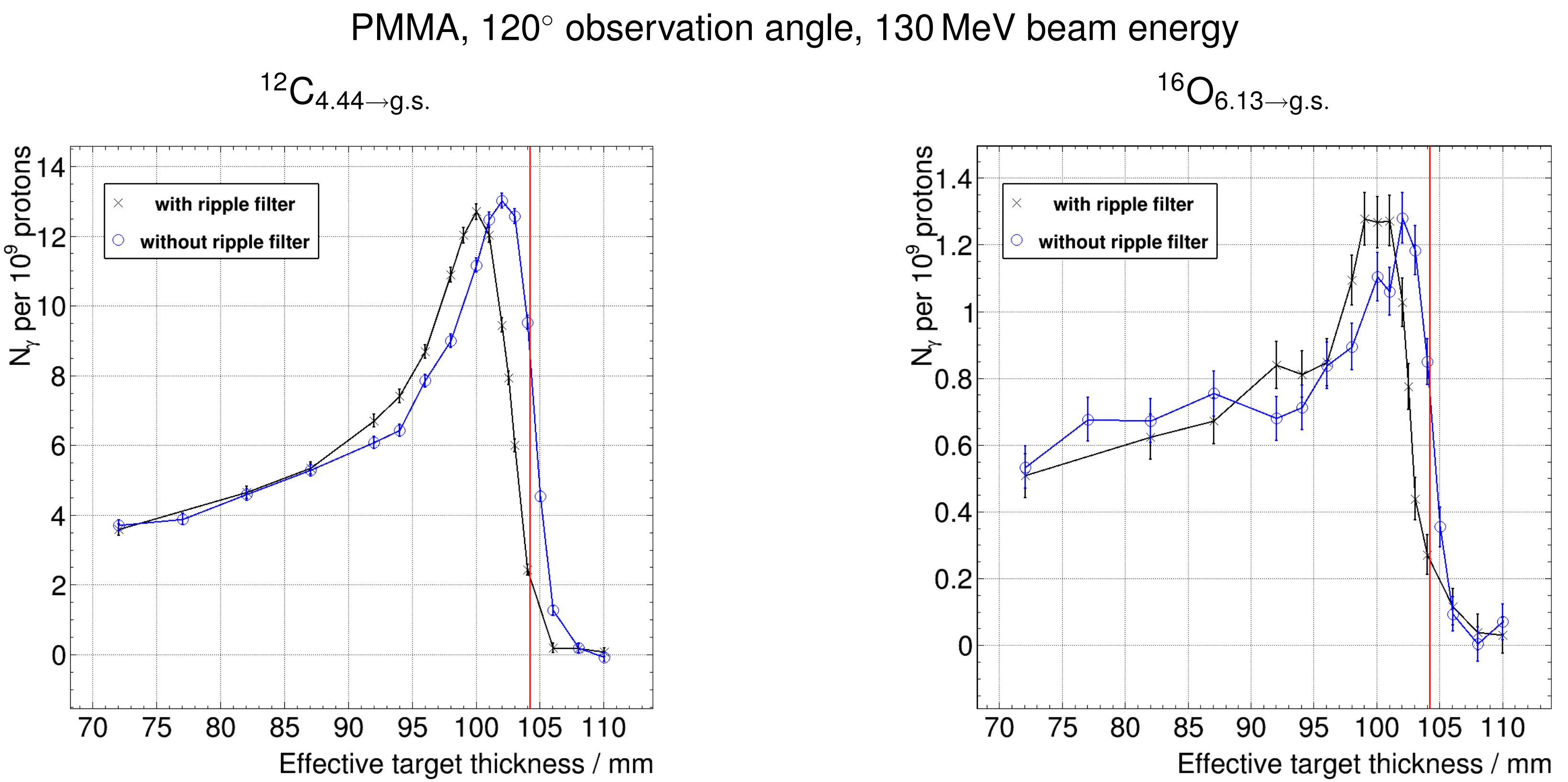
Effect of a Ripple Filter



Weber et al (1999):"Design and construction of a ripple filter for a smoothed depth dose distribution in conformal particle therapy". In Phys. Med. Biol.

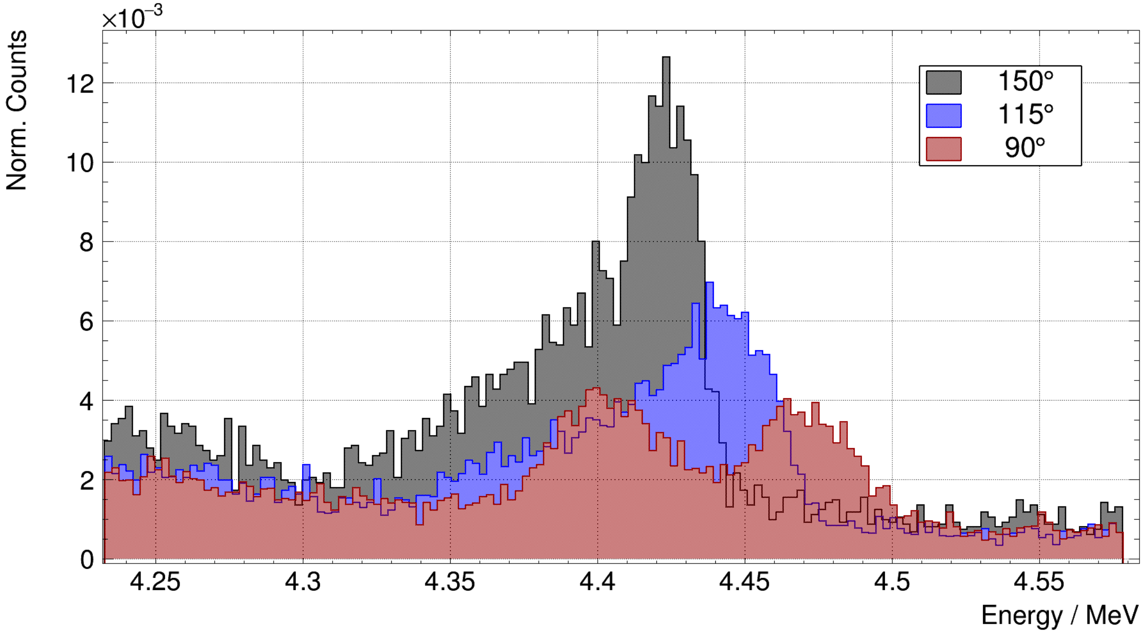
Expected effects on depth profile:
- Longitudinal shift
- Broadening?

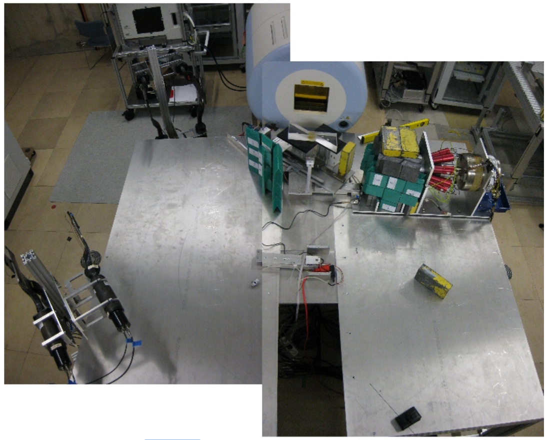
Effect of a Ripple Filter

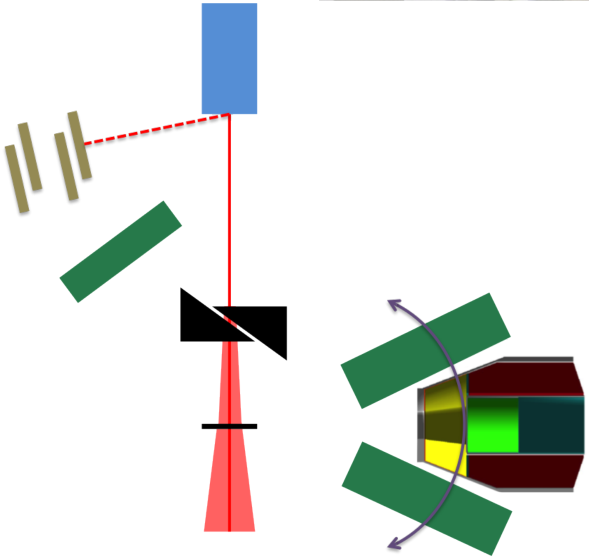


- Shift between depth profiles seen
- No broadening of gamma yield seen

Investigation on angular effects



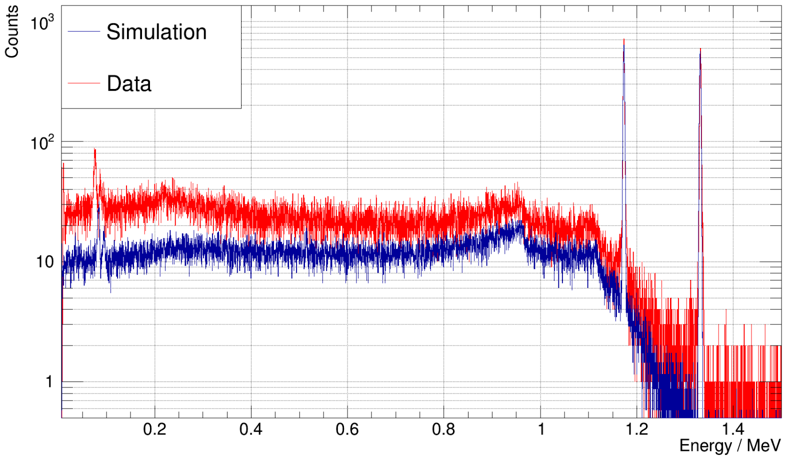


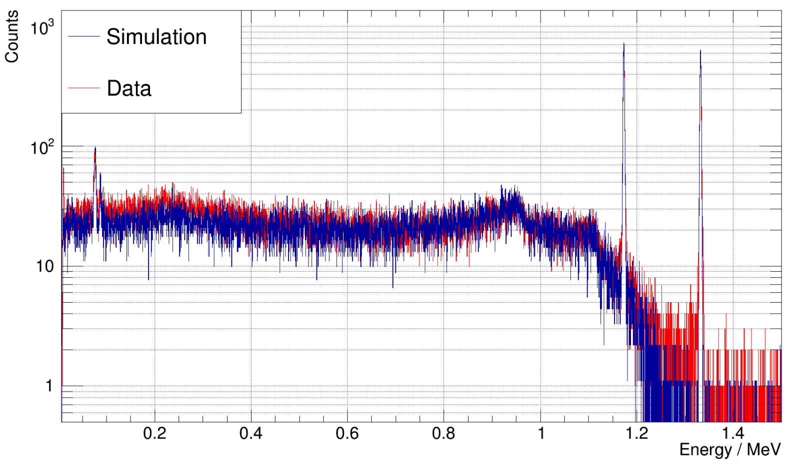


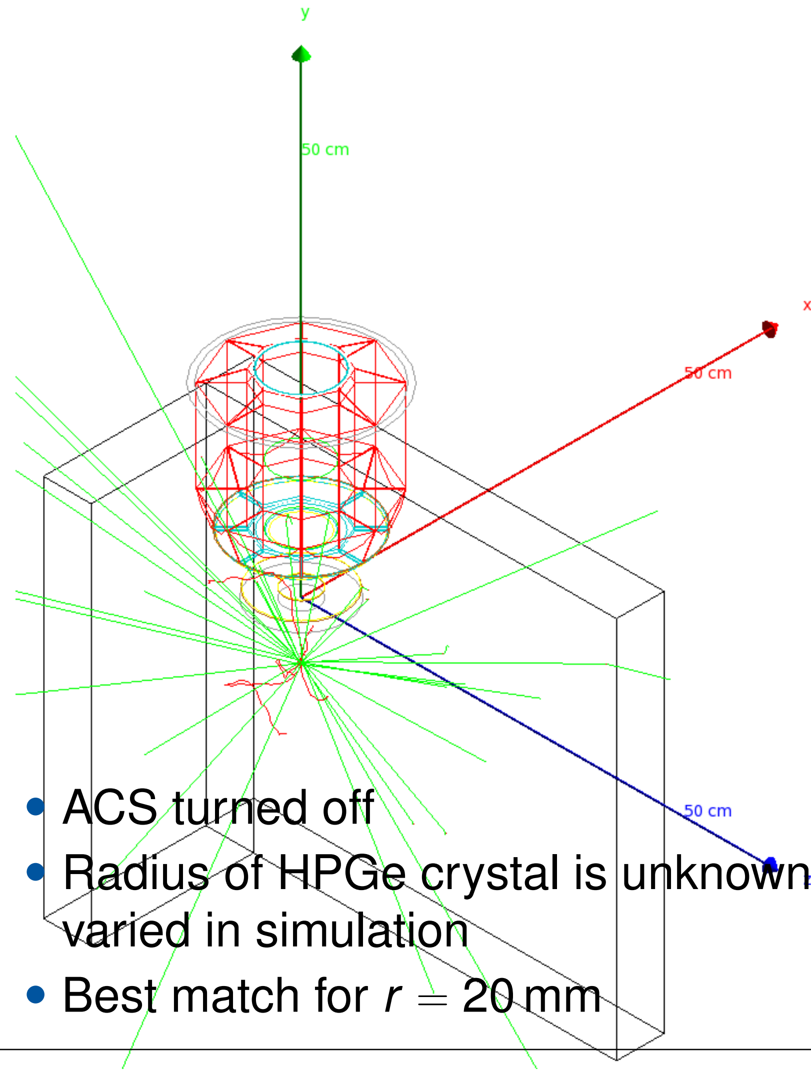
Angular dependence of

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

Simulation of ^{60}Co Source

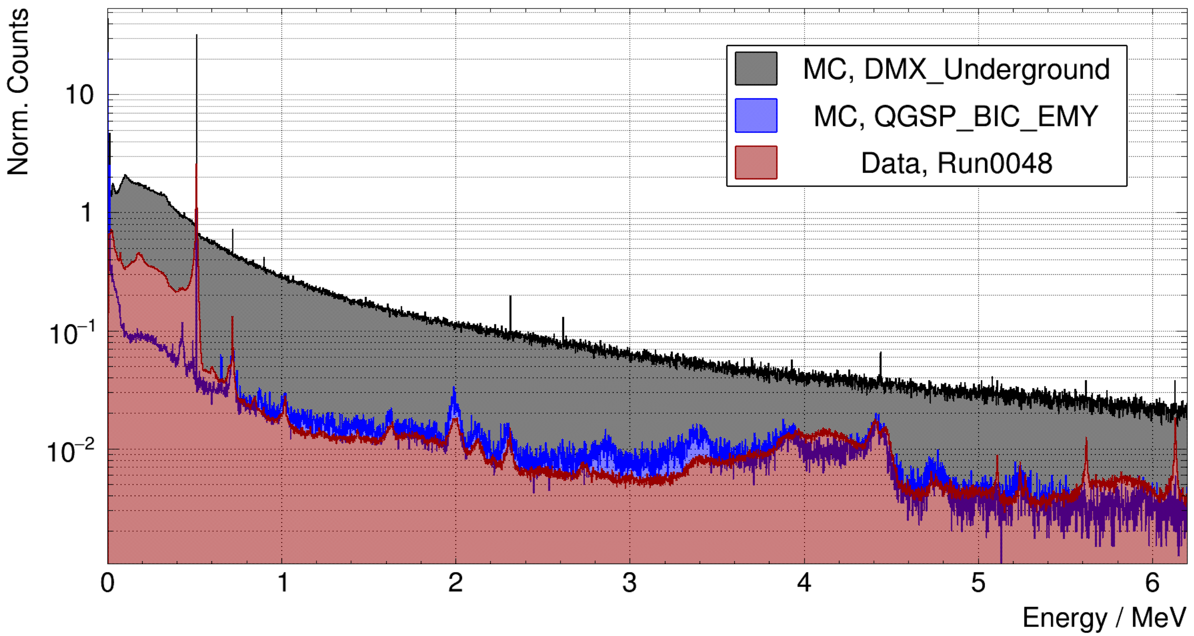


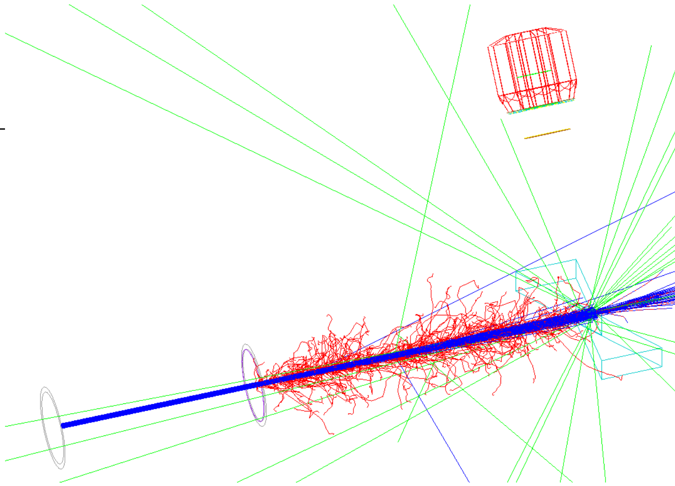


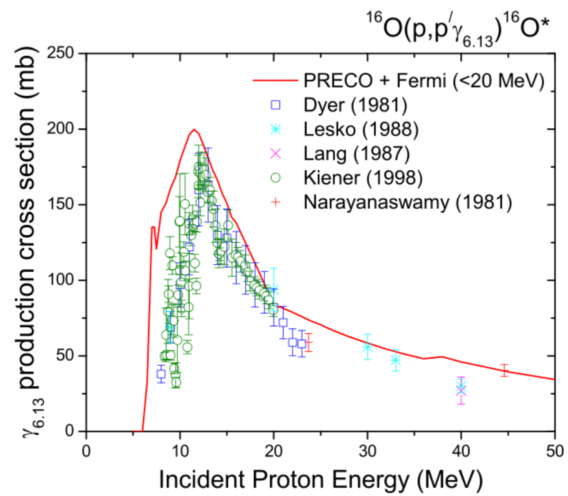


- ACS turned off
- Radius of HPGe crystal is unknown, varied in simulation
- Best match for $r = 20\,\text{mm}$

Simulation of Complete Krakow Setup







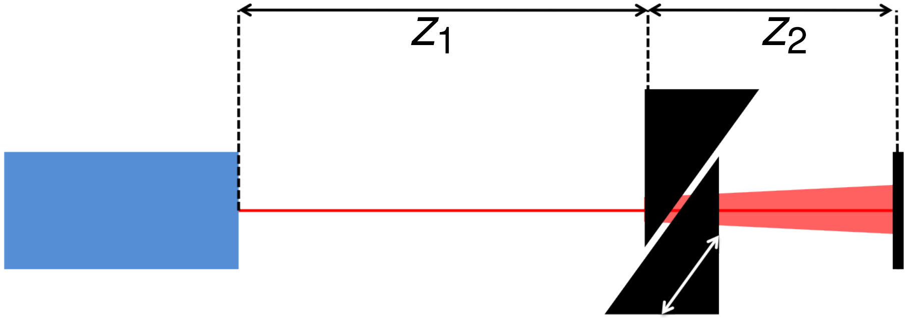
Jeyasugiththan et al (2014): Monte Carlo simulation of secondary gamma production during proton therapy for dose verification purposes.

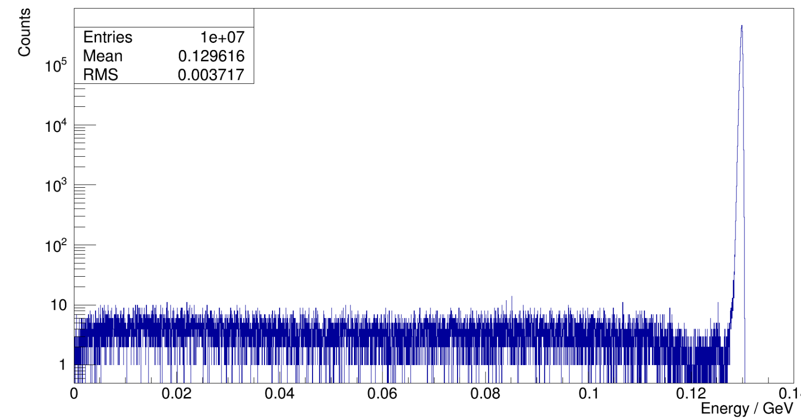
- Two different physics lists: *QGSP_BIC_EMY* and *DMX_Underground*
- Main problem: Underestimation of 6.1 MeV peak
- Literature: Exchange parts of *QGSP_BIC_EMY*

Physics Lists in GEANT4

- Physics in GEANT4 is implemented in class *Physics List*
- Pre-defined physics lists for certain applications
- *QGSP_BIC_EMY*:
  - QGSP: Quark Gluon String Precompound, hadronic model
  - BIC: Binary Ion Cascade, inelastic model for ions
  - EMY: Electro Magnetic Y, high precision for electrons, hadrons, and ions in absence of magnetic field
  - EM Physics: G4EmStandardPhysics_option3
  - Models loaded:
    - Synchroton Radiation & GN Physics: G4EmExtraPhysics
    - Decays: G4DecayPhysics
    - Hadron Elastic scattering: G4HadronElasticPhysics
    - Hadron Physics: HadronPhysicsQGSP_BIC
    - Stopping Physics: G4StoppingPhysics
    - Ion Physics: G4IonBinaryCascadePhysics
    - Neutron tracking cut: G4NeutronTrackingCut
- *DMX_Underground*:
  - Developed for dark matter experiment simulation
  - Available as: DMX Underground Advanced Example
  - Non-modular physics list
- Differences: energy smearing, 6.1 MeV peak, Doppler broadening

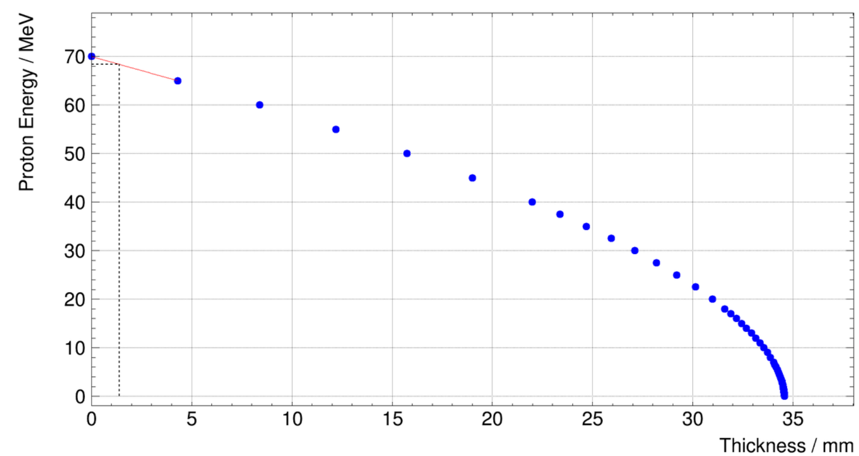
Target Thickness Correction



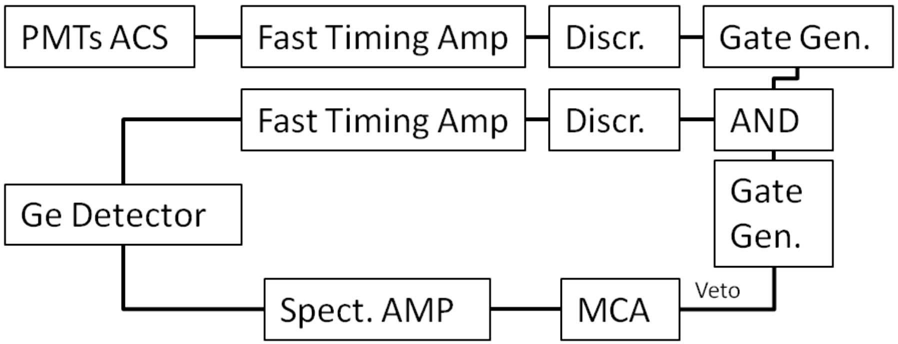


Correction of target thickness:

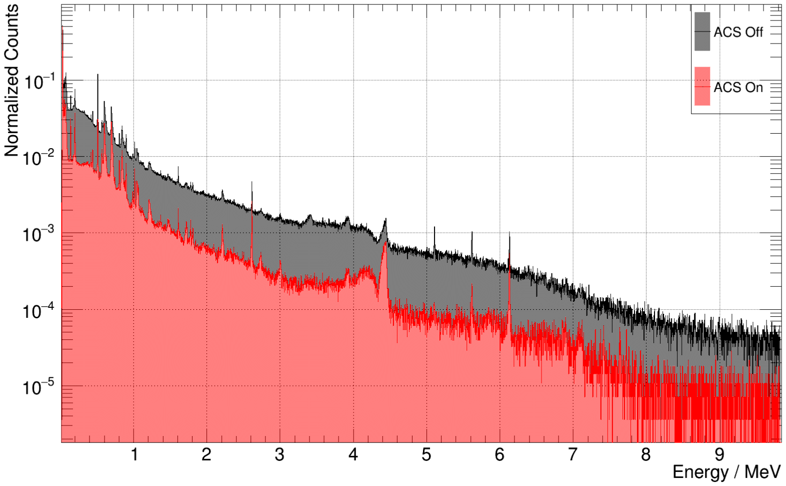
- Simulated phase space file from HIT for energy after exit foil
- Determine equivalent path length in air for energy loss using SRIM
- Add path through air in front of wedges
- Convert to equivalent path length in target
- Add wedge thickness
- Convert to energy after wedges
- Convert to equivalent path length in air
- Add path after the wedges
- Convert to energy before slice
- Convert to equivalent path length in target material
- Add half of slice thickness

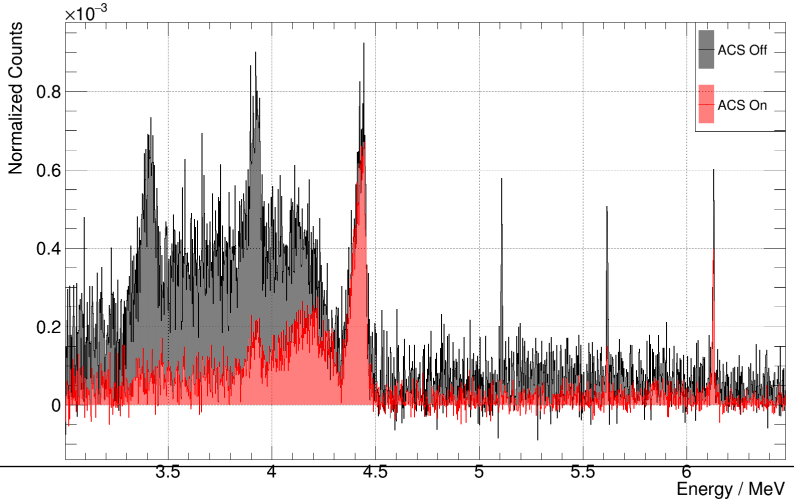


Performance of Active Compton-Shield



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



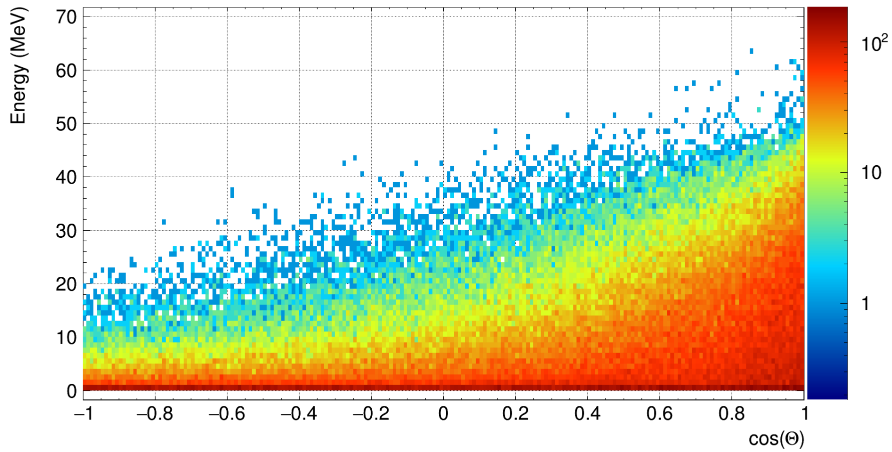


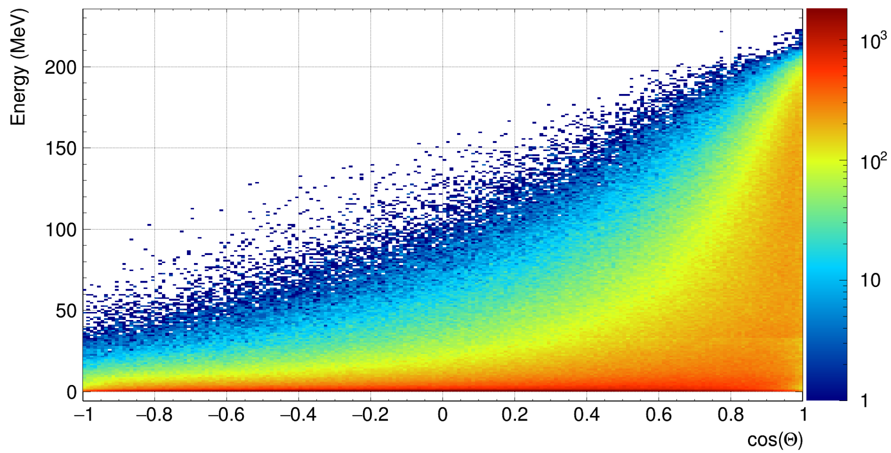
Simulation of Neutron Background at Higher Energies

- increase in number of neutrons
- number of “interesting” photons is constant

⇒ worse signal-to-background ratio
⇒ improved shielding necessary

Energy / MeV	70	150	230
Number of neutrons	17158	107048	240727





Normalization

Normalization to correct for:

- Measurement time
- Beam intensity
- Detector dead time

$$N_{\text{normalized}} = \frac{N_{\text{raw}}}{N_{\text{Proton}}} \cdot \frac{1}{c_{\text{Dead Time}}} \tag{1}$$

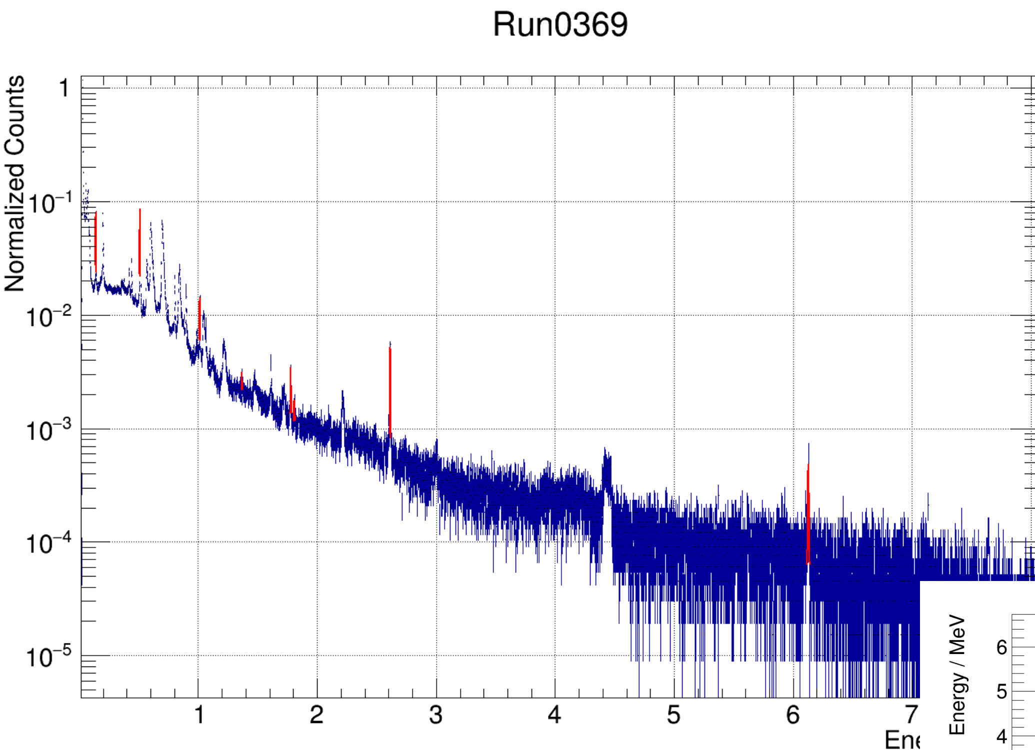
$$c_{\text{Dead Time}} = 1 - \frac{t_{\text{break}} + t_{\text{extraction}}}{t_{\text{extraction}}} \cdot \frac{t_{\text{dead}}}{t_{\text{real}}} \tag{2}$$

$$N_{\text{Proton}} = f_{\text{norm}} \cdot N_{\text{BCM}} \tag{3}$$

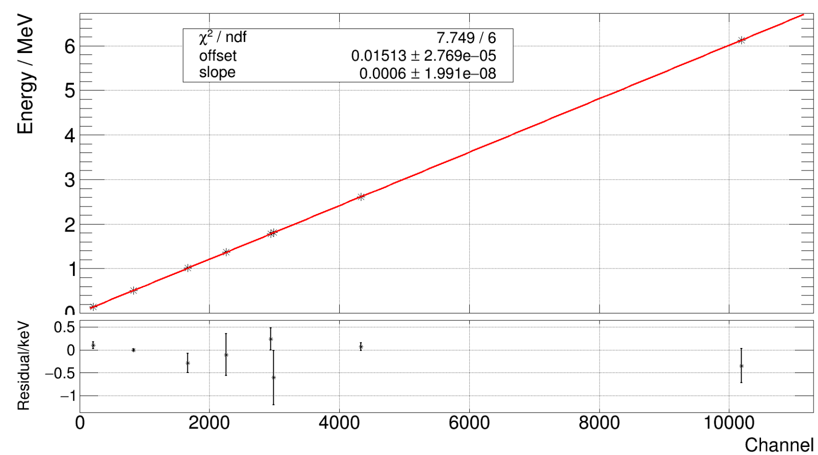
Needed:

- Beam Current Monitors
- Dead time of detector
- Information on synchrotron working cycle
- HIT Phase-Space files to determine f_{norm}

Energy Calibration

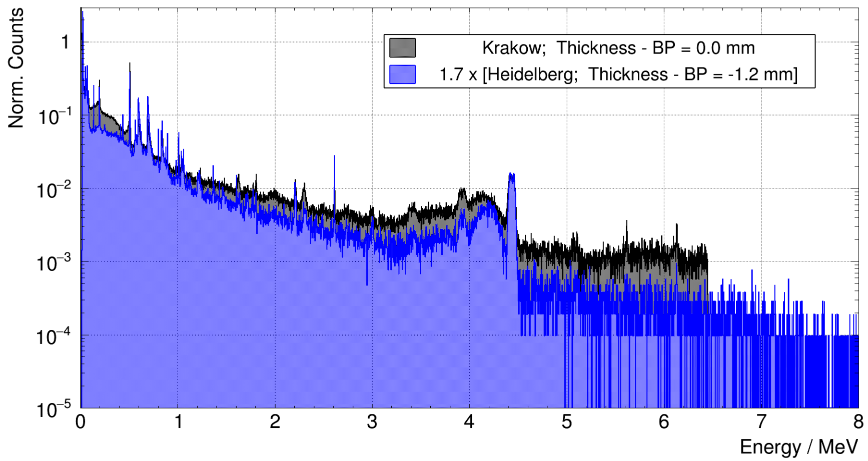


- $^{74}Ge(n,\gamma_{0.13988\,MeV})^{75}Ge$
- $\gamma_{0.510999\,MeV}$, annihilation
- $^{27}Al(n,n'\gamma_{1.0144\,MeV})^{27}Al$
- $^{27}Al(p,\alpha\gamma_{1.3688\,MeV})^{24}Mg$
- $^{27}Al(n,\gamma_{1.7791\,MeV})^{28}Al$
- $^{27}Al(n,d\gamma_{1.8084\,MeV})^{26}Mg$
- $^{208}Pb(n,n'\gamma_{2.61451\,MeV})^{208}Pb$
- $^{16}O(p,p\gamma_{6.12863\,MeV})^{16}O$



- Each run calibrated individually
- Systematic shifts of max. 100 eV over whole beam time

Comparison Spectrum Krakow Heidelberg

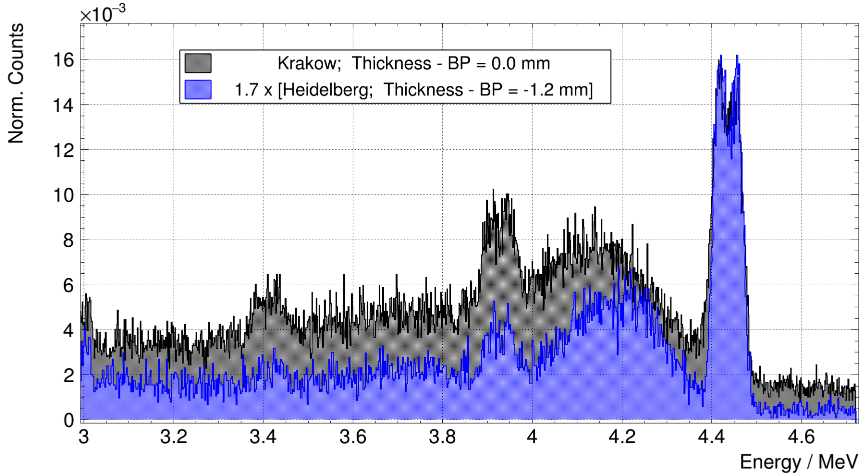


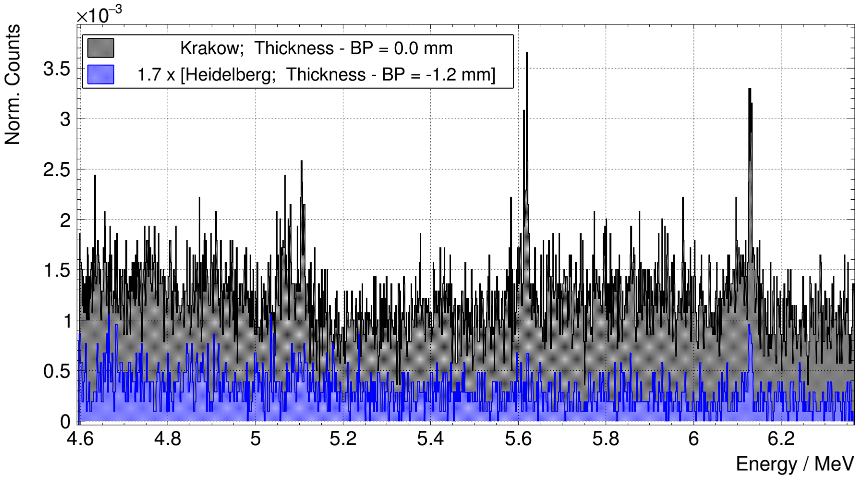
Test-beams in

- Krakow: 2013 and 2014
- Heidelberg: July 2015

Improvements in

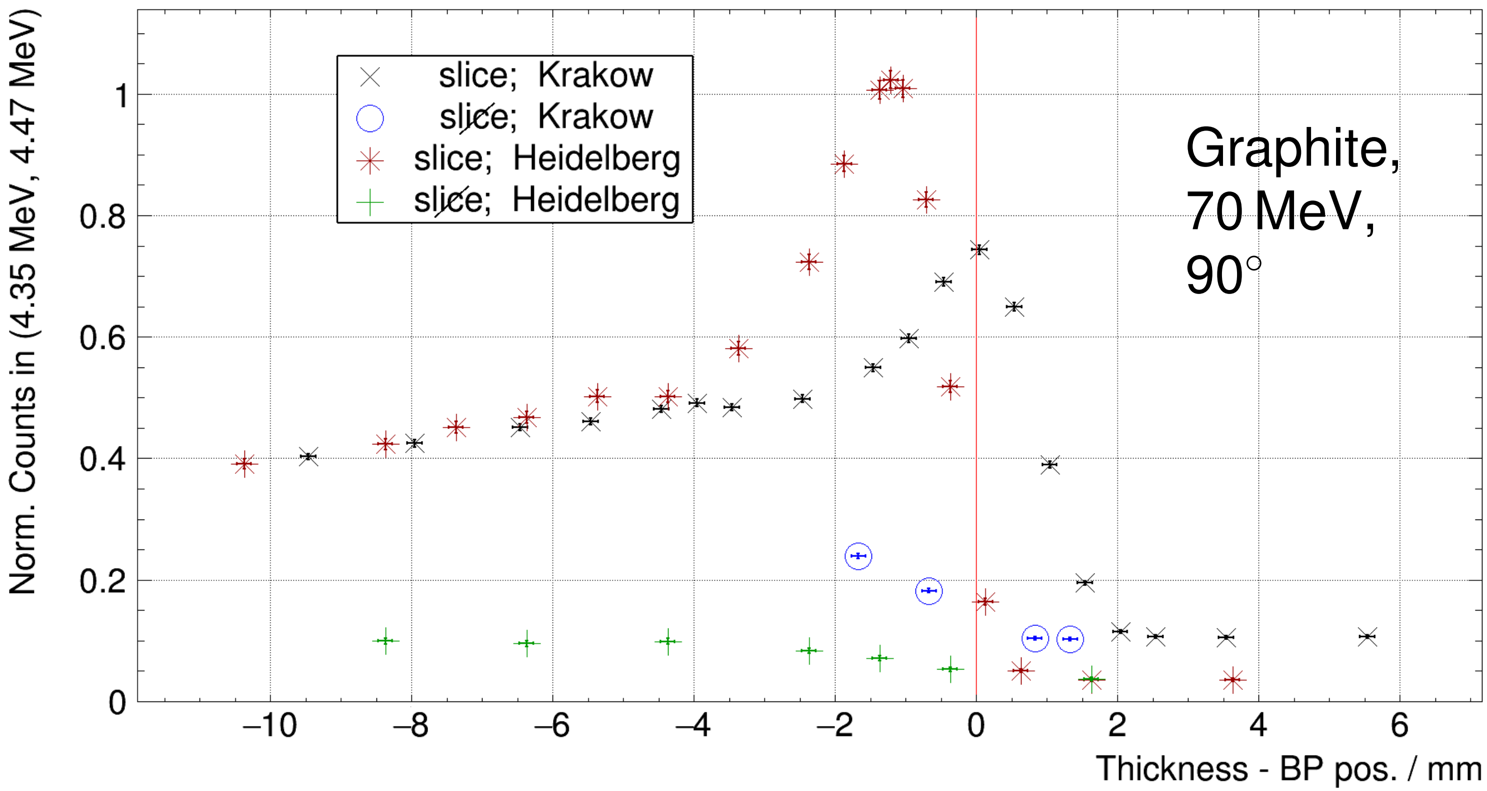
- ACS performance
- Background shielding





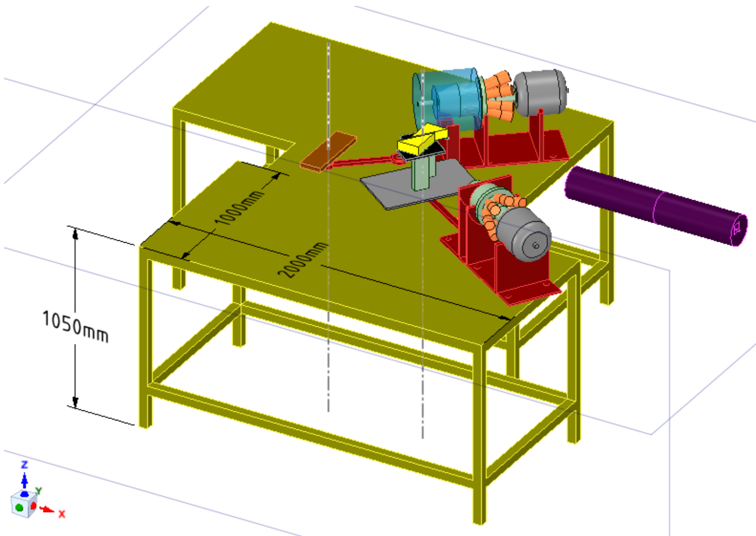
70 MeV, Carbon target

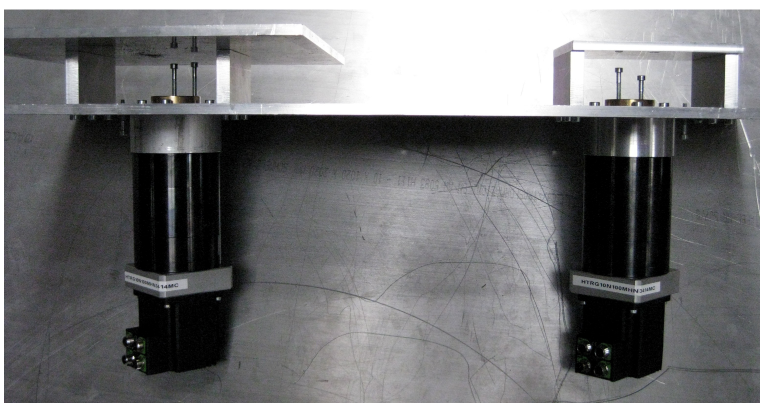
Comparison of Gamma Yield Heidelberg-Krakow

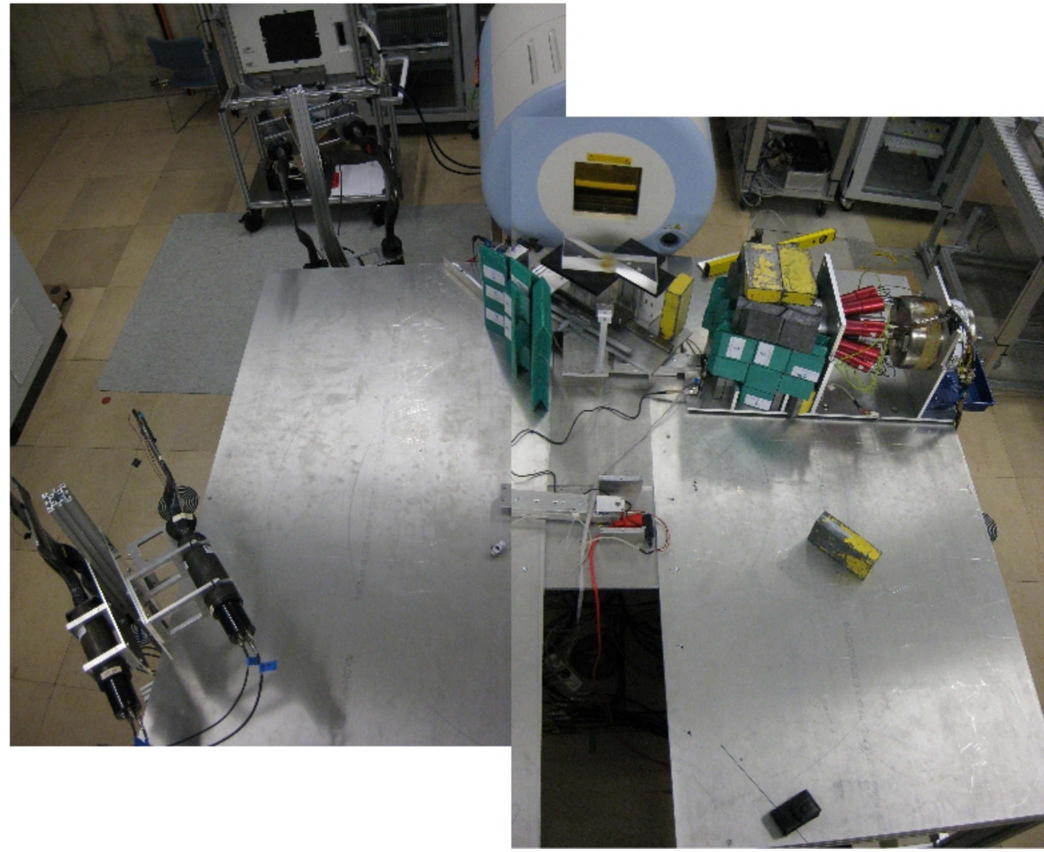


- Improved S/N-ratio
- Origin of shift (∼1.2 mm): Calibration of Target Moving System?

Detector Rotation System

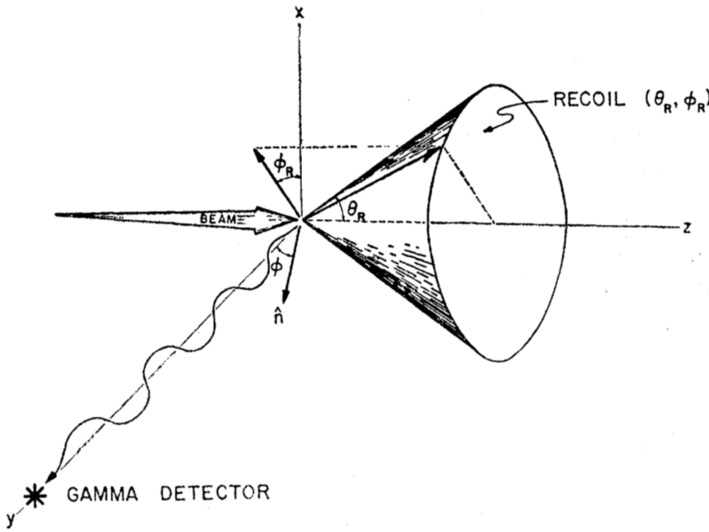




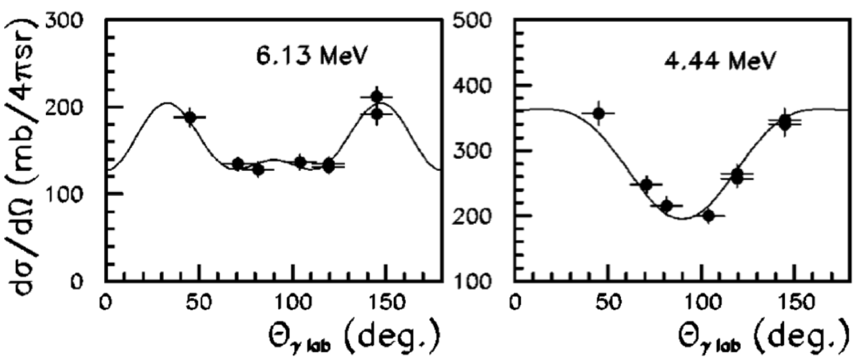


- 2 rotation axes with JVL motors and gear system (1:100)
- Rotation of detector + lead shielding

Motivation: Angular Distribution



Kolata et al (1967): "Excitation Energy of the First Excited State of ^{12}C, and Observation of a Coherent Doppler Effect".



Kiener et al (1998): " γ-ray production by inelastic proton scattering on ^{16}O and ^{12}C".

- Incoming and outgoing protons define scattering plane
- Axis of quantization perpendicular to this plane
- Angular distribution with respect to incoming beam:

$$W(\theta) = \sum_{l=0}^{l_{max}} a_l P_l(\cos\theta)\,; \quad l \text{ even} \qquad (4)$$

- Non-flat angular distribution for $^{12}C(p,p\gamma_{4.4\,MeV})^{12}C$ and $^{16}O(p,p\gamma_{6.1\,MeV})^{16}O$