The impact of secondary fragments on helium CT

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[6] SCIPP, University of California at Santa Cruz,, Santa Cruz, CA, USA

Team: Biomedical Physics in Radiation Oncology

- Joint project with Dr. Pierluigi Piersimoni
- Project collaborators:
  U.S. pCT collaboration
  Heidelberg Ion-Beam Therapy Center
- Biomedical Physics in Radiation Oncology (Prof. Joao Seco):
  Model early radiation effects, Prompt gamma, **Particle Imaging**

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Overview

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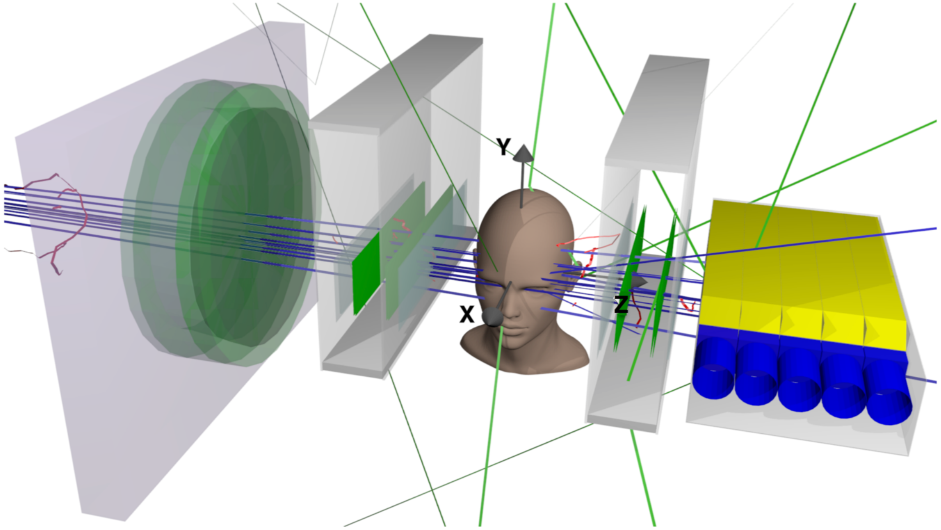
Introduction



- Piersimoni *et al.* (2017)

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Rationale for helium imaging

- Lower multiple Coulomb scattering compared to protons ($\sigma_{sc}{}^{He} = 0.5\sigma_{sc}{}^{p}$)

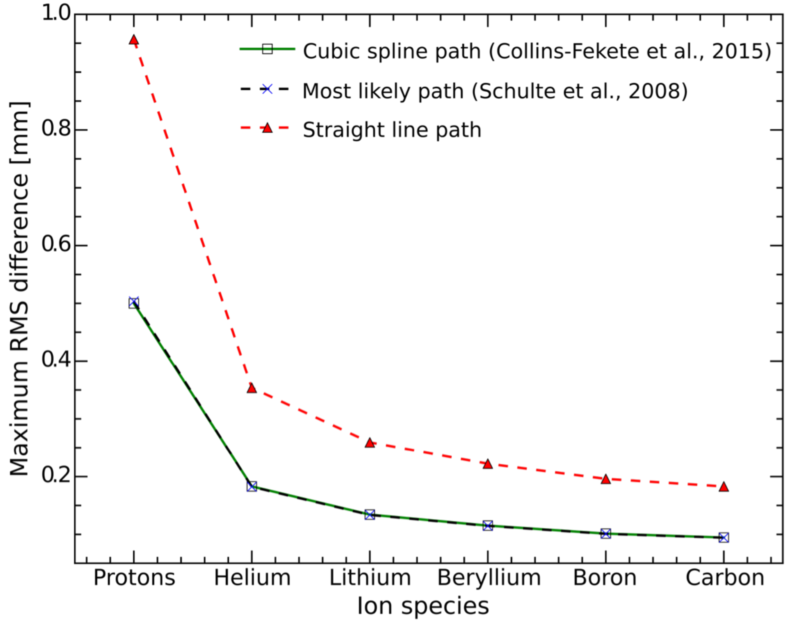
➡ Higher achievable spatial resolution[1,2]

- Lower energy/range straggling compared to protons ($\sigma_{st}{}^{He} \cong 0.5\sigma_{st}{}^{p}$)

➡ Higher achievable precision[3]

- Lower dose and less fragmentation compared to heavier ions[4]

- Rising interest in helium ion therapy[4]



- RMS difference between different path estimates and MC ground truth for light ion species at fixed range (~26cm).[1]

[1] Collins-Fekte et al. (2017); [2] Piersimoni et al. (2018); [3] Gehrke et al. (2018); [4] Mairani et al. (2016)

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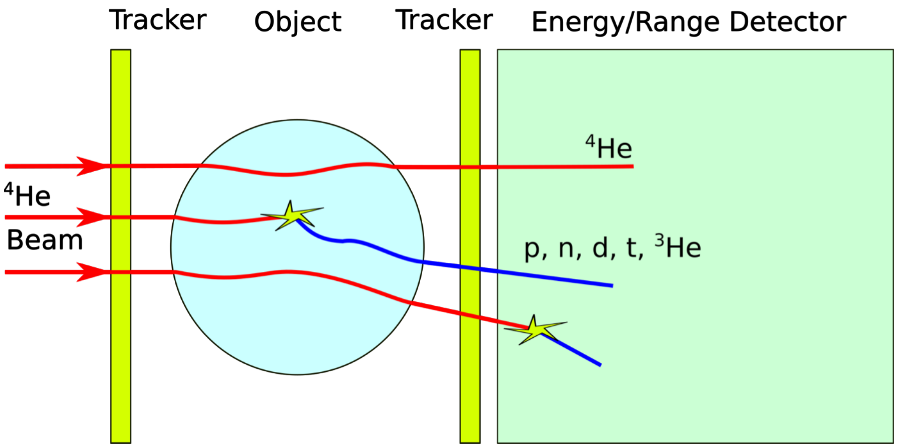
Fragmentation events

- *Target* and *projectile* fragmentation
- Projectile fragments only receive a minor shift in velocity/direction[1,2]
- Fragmentation in the object and the detector possible
- Projectile fragments readily detected by the scanner, not readily identified



- Schematic depiction of the mixing of fragments and primary beam energy loss in helium CT.

→ **Method to remove fragmentation events required**

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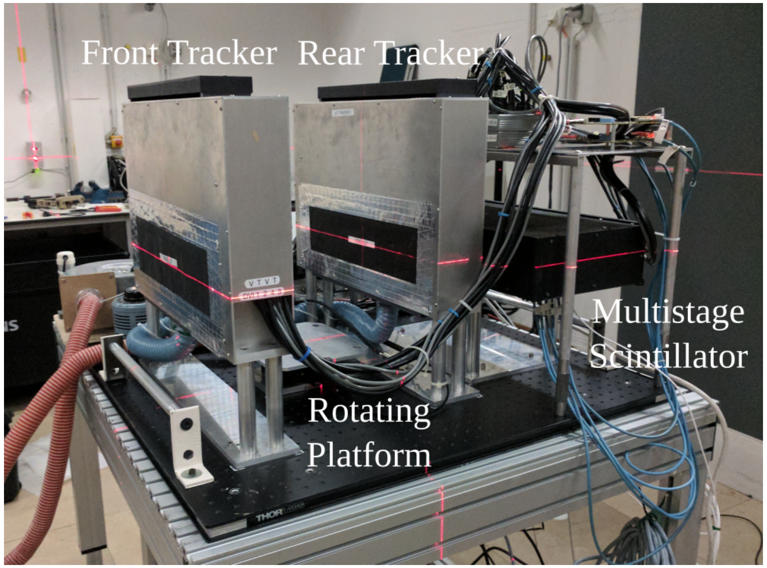
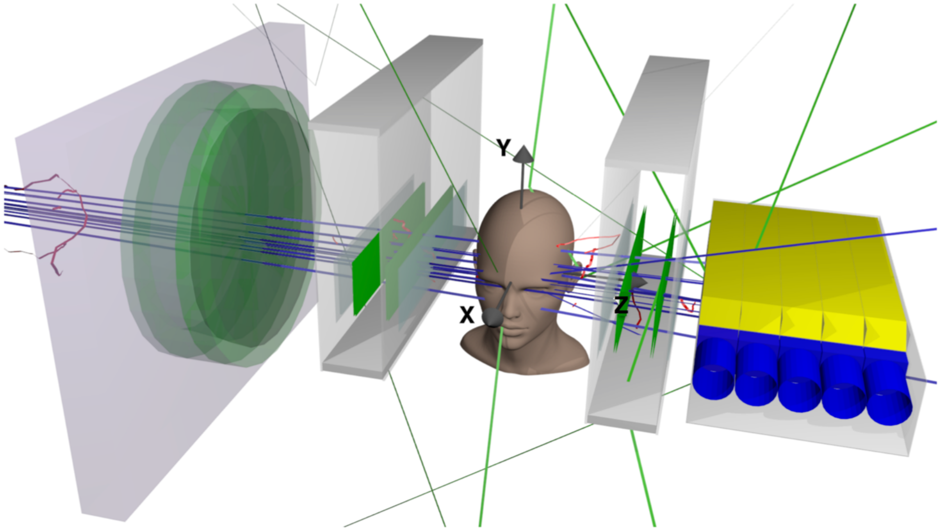
Operating a pCT prototype with helium beams

Experiment



- The U.S. pCT collaboration prototype installed at the HIT beam line dedicated to experiments.

TOPAS MC simulation



- TOPAS implemented detector geormetry.[1]

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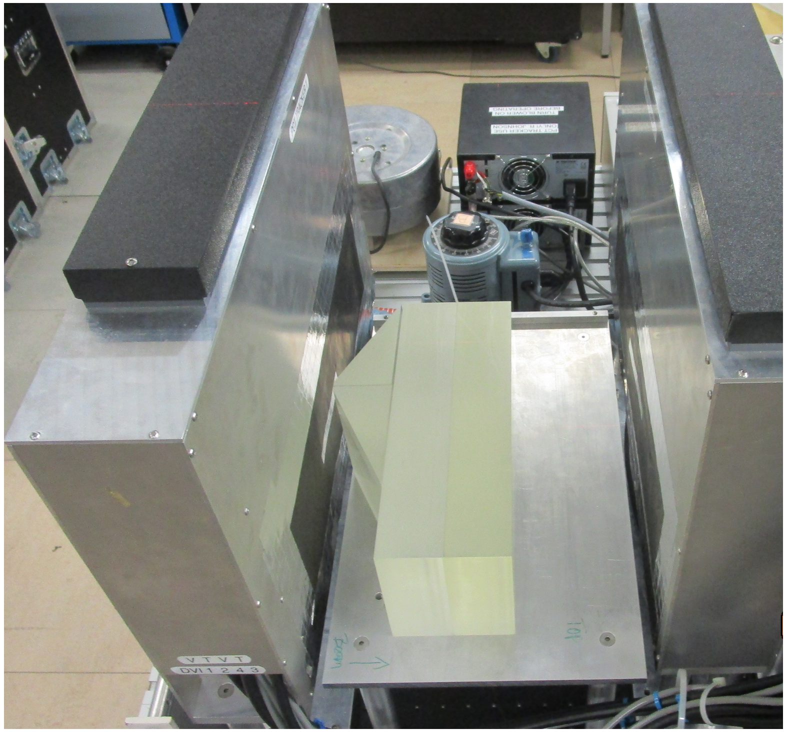
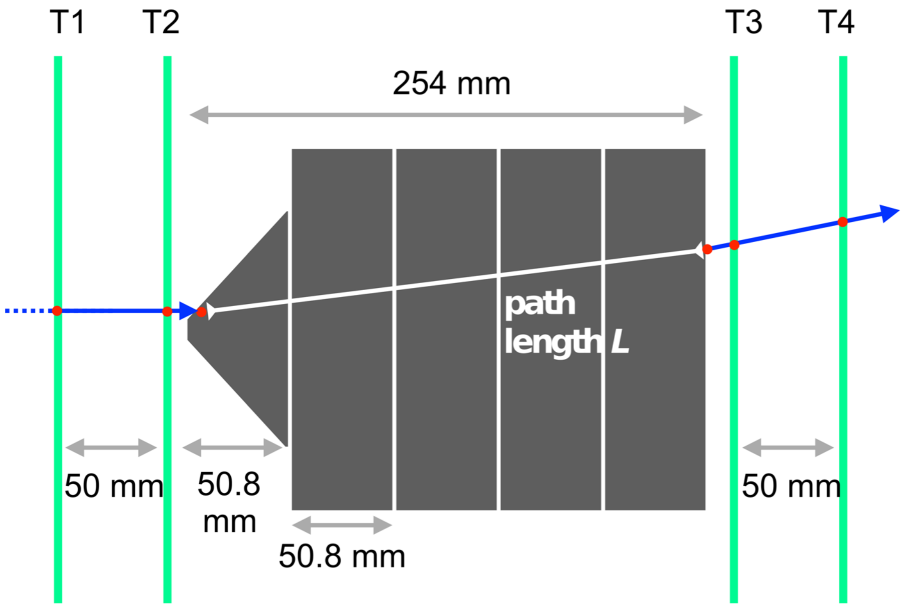
Calibration



- The Calibration setup as performed at HIT.



- Depiction of the wedge calibration procedure.[1]

[1] Piersimoni et al. (2018);

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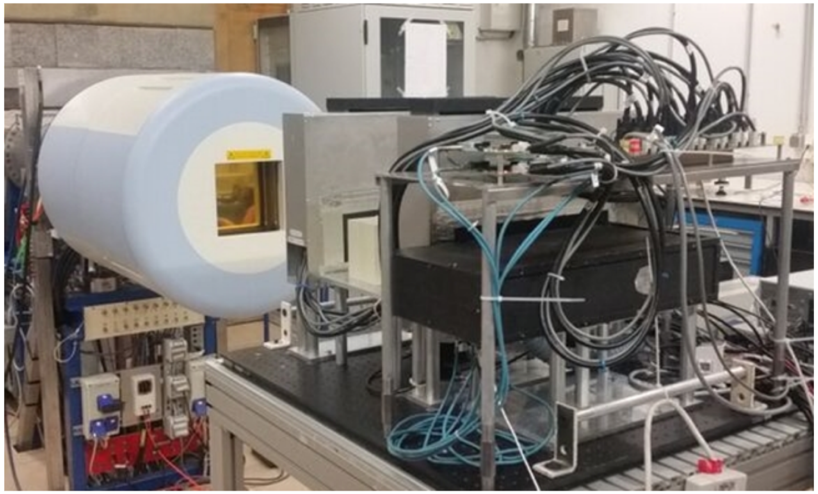
Beam settings and scanning experiment

- Experiments conducted at the beam line dedicated to experiments at HIT [1]

- Experiment: Raster scanning (10.8 mm FWHM spots)
  Simulation: Flat ideal source

- Experiment: $\sim 2.5 \cdot 10^6$ part./proj. (~ 800kHz)
  Simulation: $2 \cdot 10^6$ part./proj
  $E_{in} = 200\ MeV/u$

- 90 projections at $4°$ angular step [2]



- Beam nozzle dedicated to experiments.

[1] Harberer et al. (2004)

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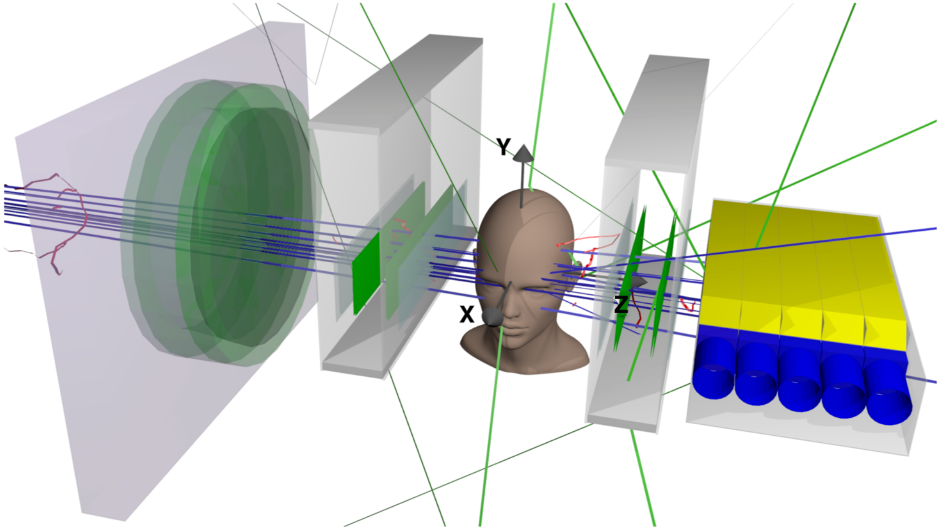
Filtering of Fragments



- Piersimoni *et al.* (2017)

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ΔE – E Technique

Idea: Use the 5 stage energy/range detector as ΔE – E telescope!

- $dE/dx = f(Zp, Ap)$
- Energy loss measured in thin ΔE stage, residual energy E in a thick absorber after
- Enables particle identification in mixed radiation beams

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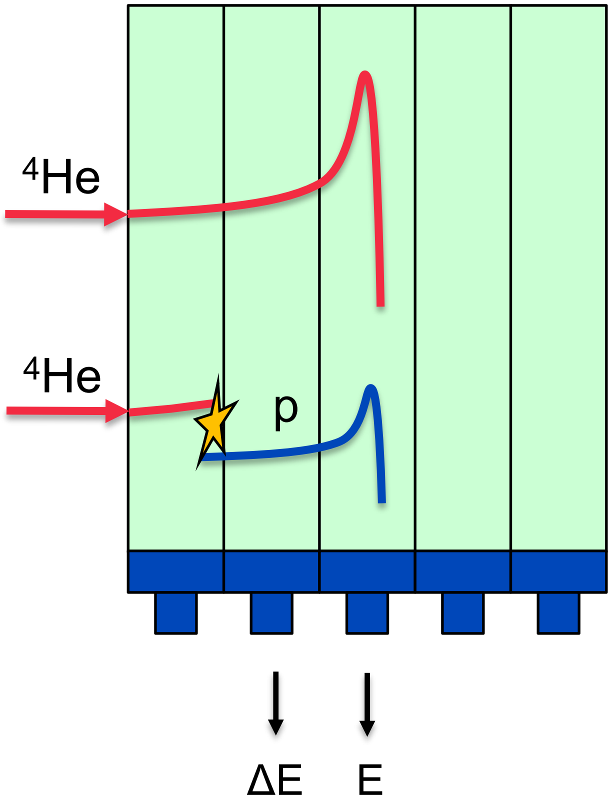
ΔE – E Technique

Idea: Use the 5 stage energy/range detector as ΔE – E telescope!



- E defined as the energy deposit in the stage where the particle stops
- ΔE defined as the energy deposit for the same event in the adjacent stage
- Parametrization of the primary helium line in the spectrum enables filtering

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Filtering workflow

1. No filtering of fragmentation/nuclear interaction events
2. Threshold filter [1]
3. ΔE-E filter

[1] used as standard with the pCT prototype;

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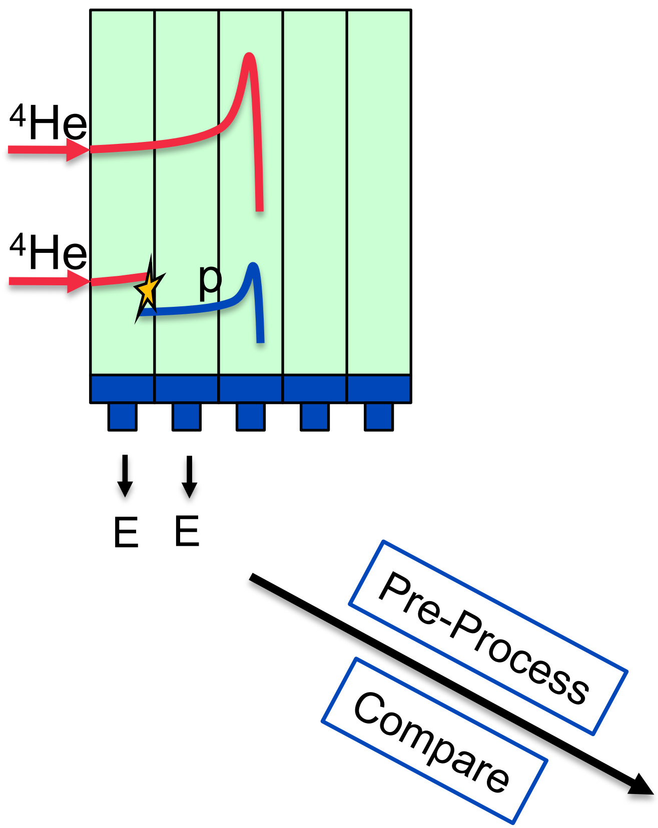
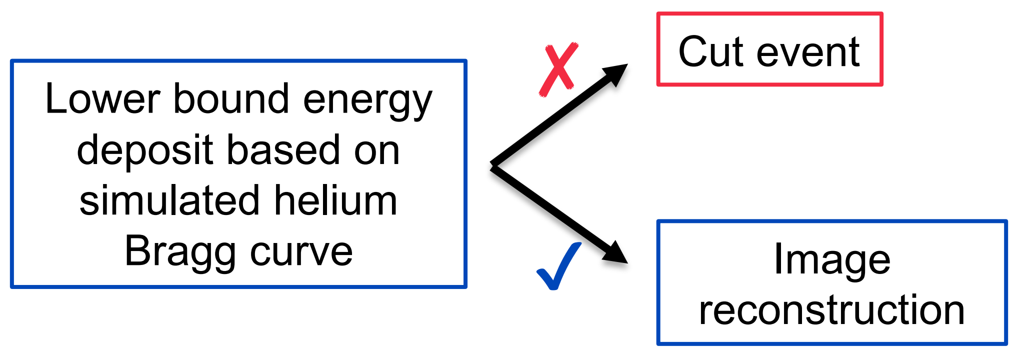
Filtering workflow: Threshold filter [1]





[1] used as standard with the pCT prototype;

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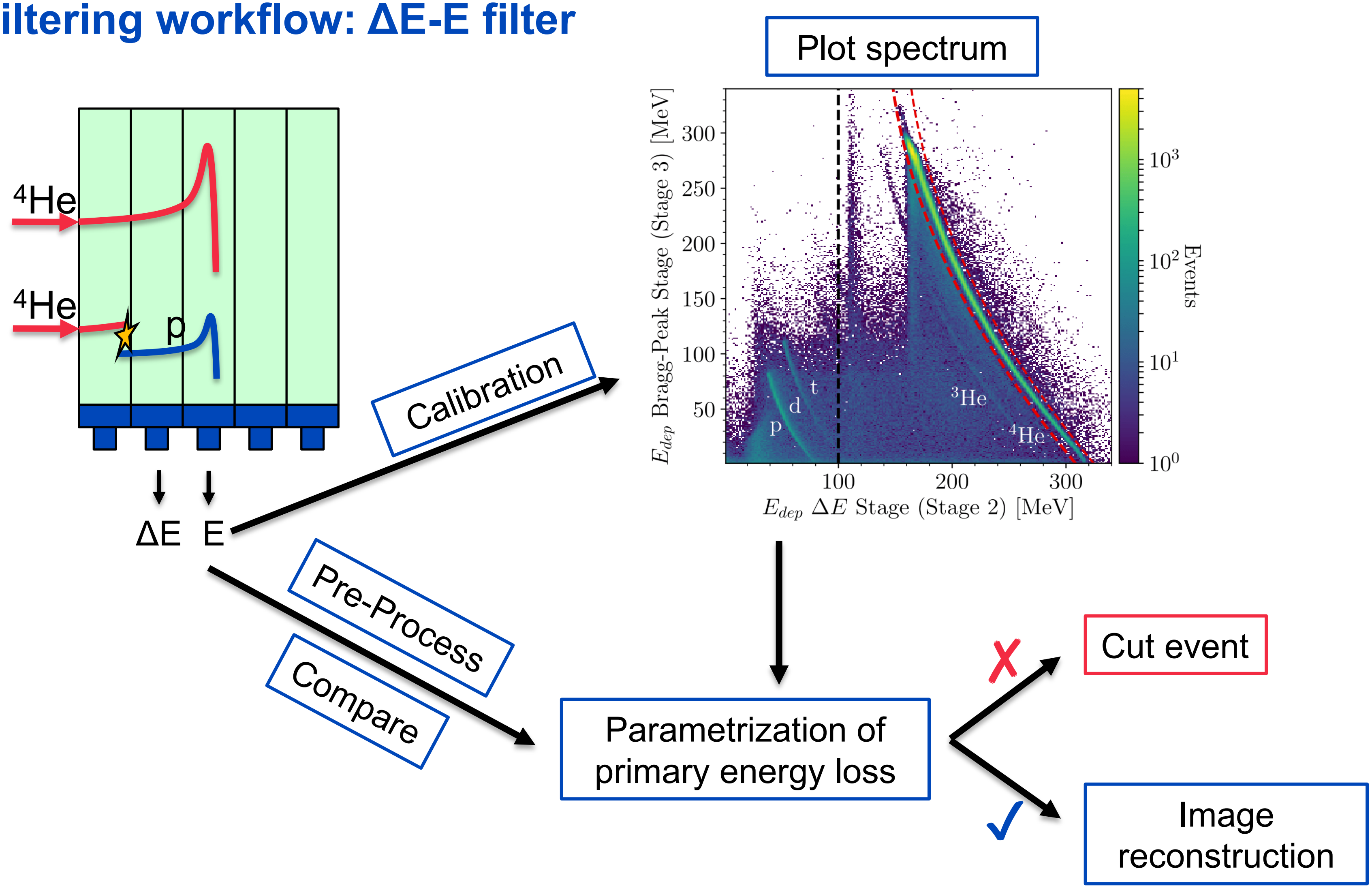
Filtering workflow: ΔE-E filter



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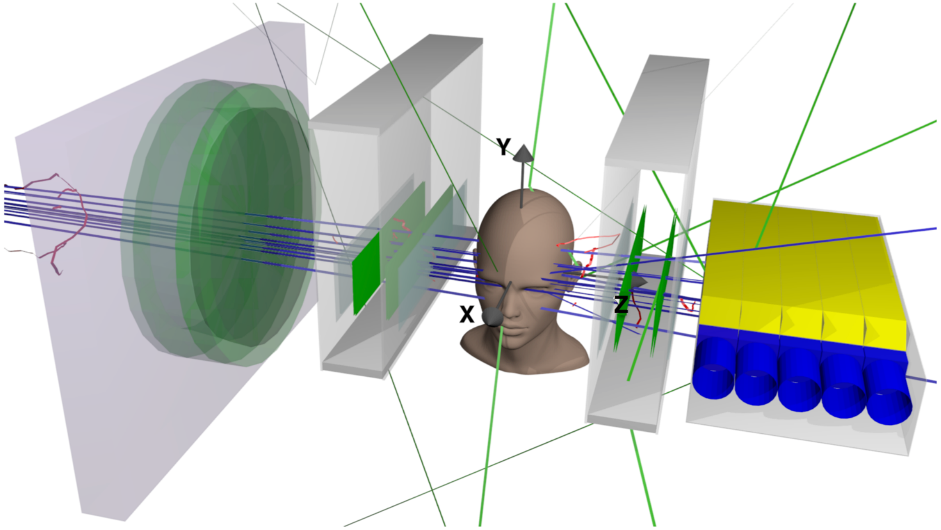
Results



- Piersimoni *et al.* (2017)

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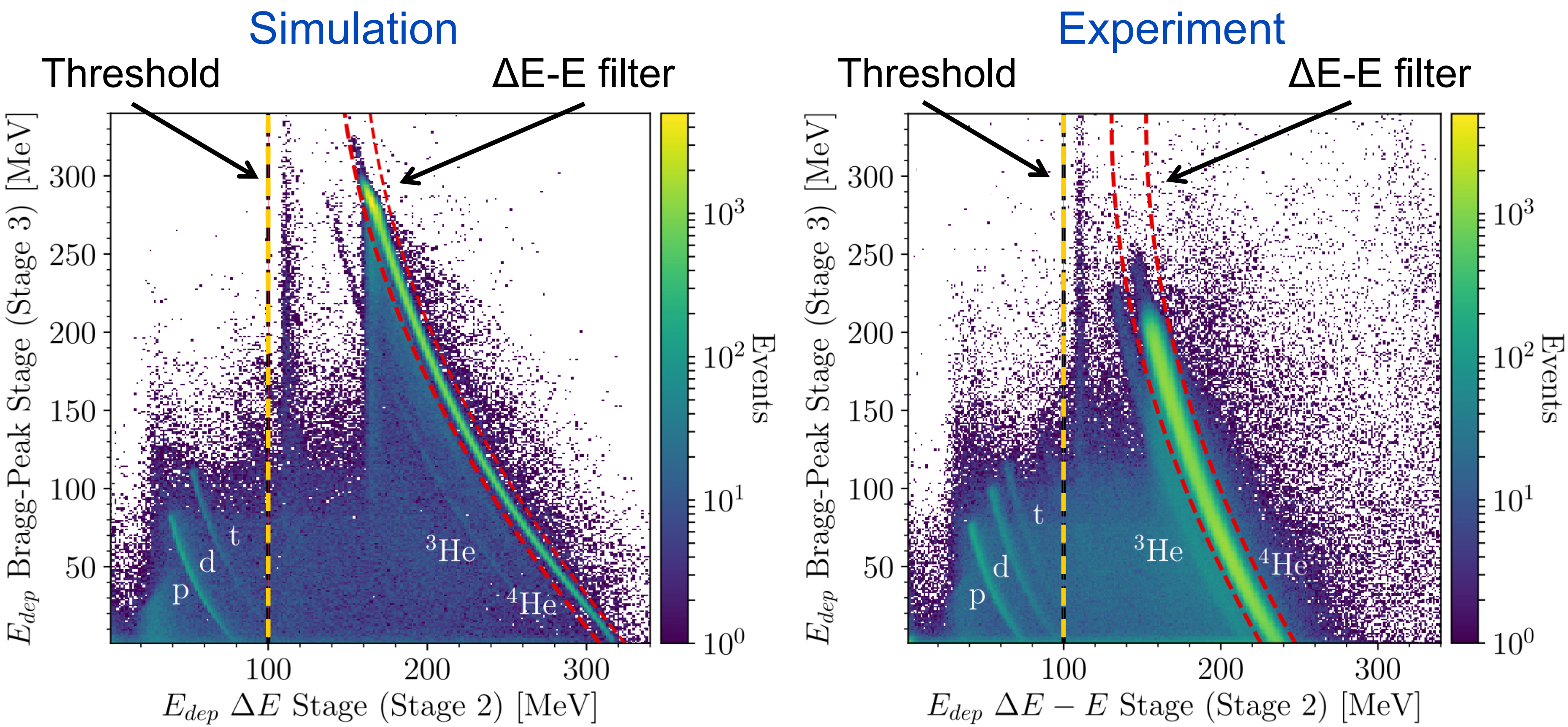
ΔE-E spectra



- Simulated ΔE-E spectrum with threshold filter (dashed black) and ΔE-E filter (dashed red).
- Experimental ΔE-E spectrum.

- Mauscript in review by PMB

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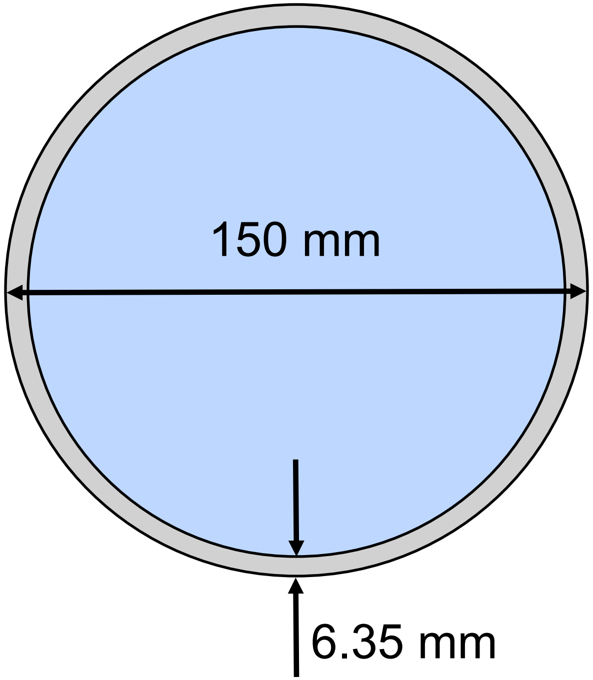
Water phantom



- Schematic depiction of the Water phantom

- Hollow plastic cylinder filled with purified and degasified water (G4_WATER in simulation)

- 150 mm diameter, 6.35 mm shell thickness, 6.35 mm top and bottom seals

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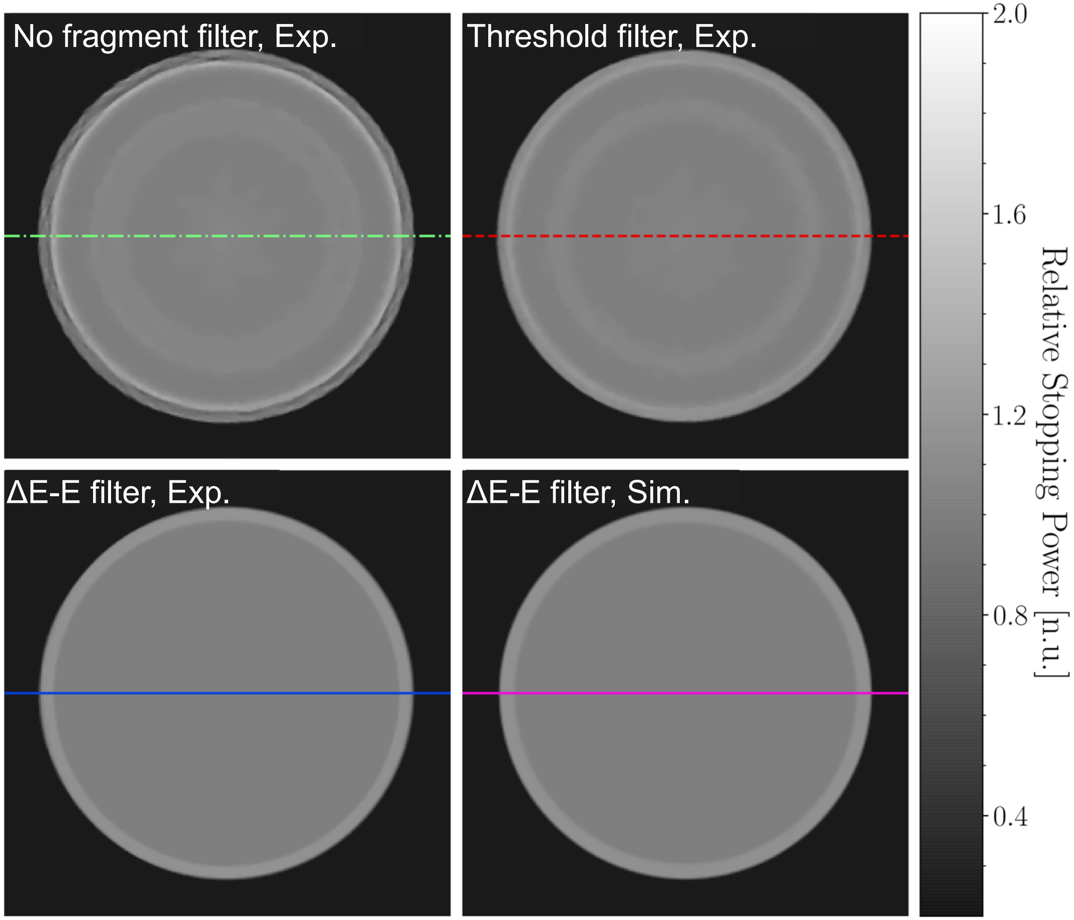
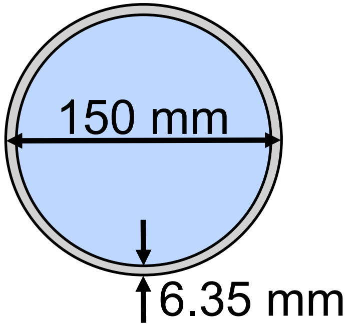
Water phantom





- HeCT reconstructed images of the water phantom with different filtering settings.

- Mauscript in review by PMB

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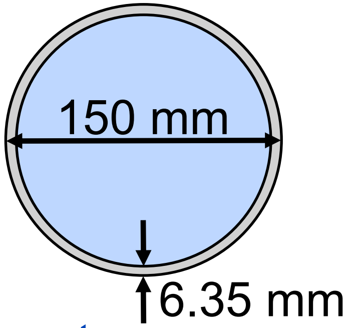
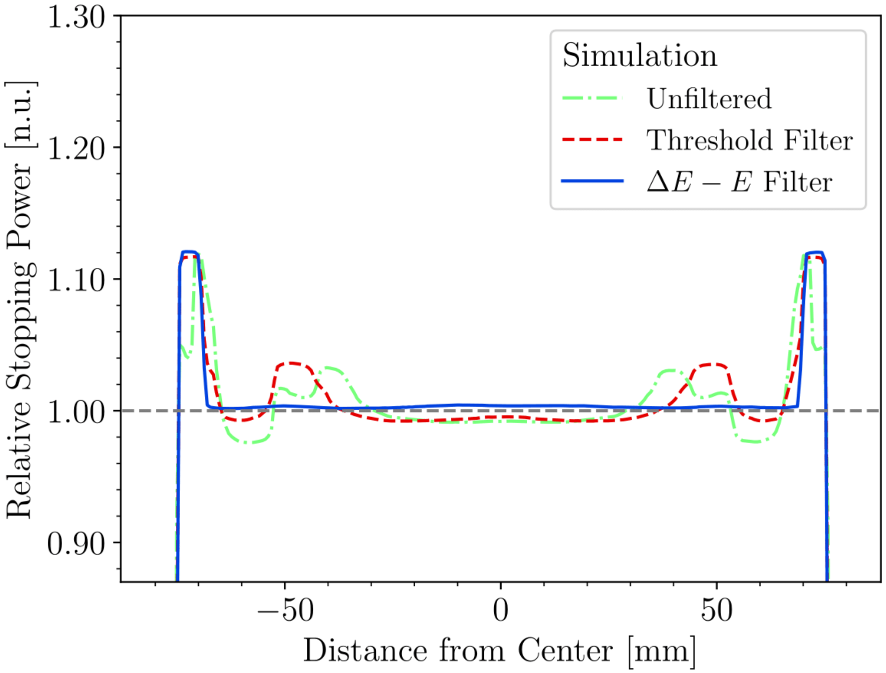
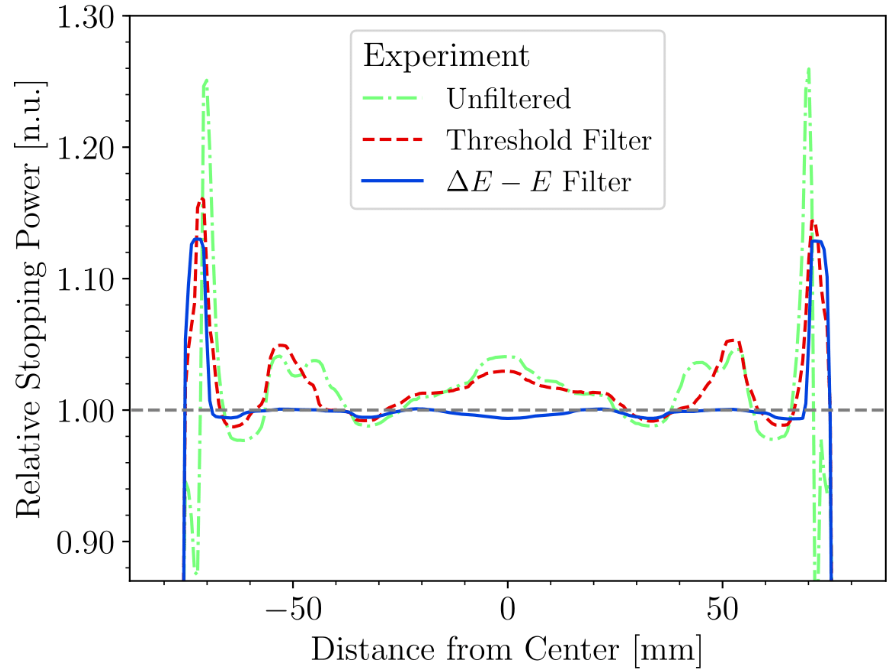
Water phantom



Simulation



Experiment



- Traverse profile of the HeCT reconstructed simulated water phantom.
- Traverse profile of the experimental HeCT.

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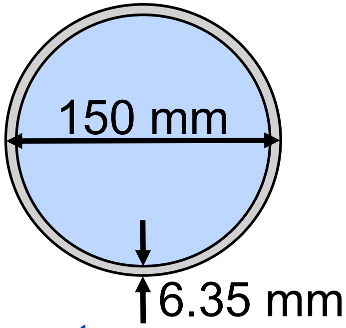
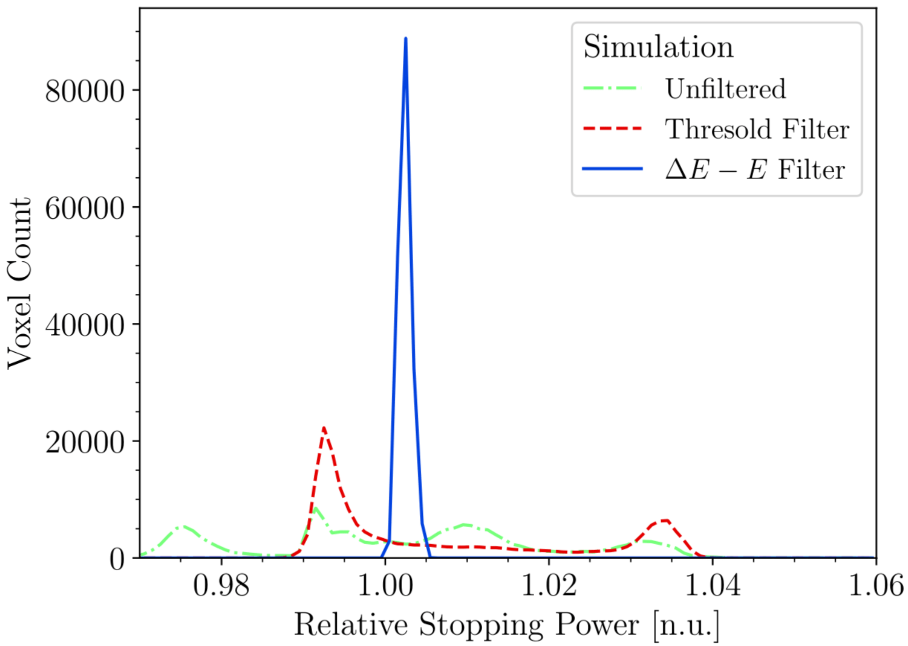
Water phantom

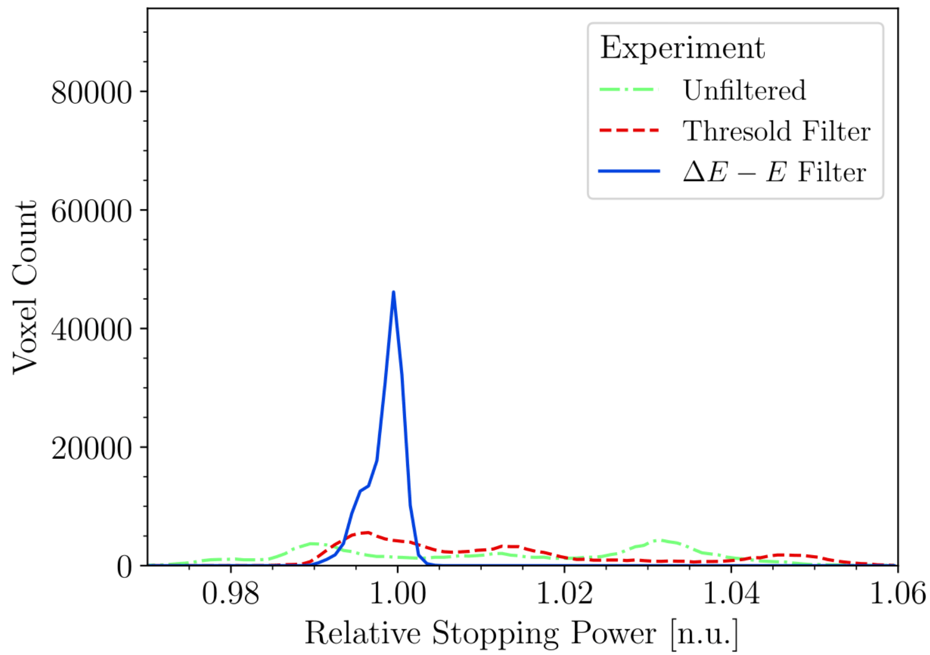


Simulation



- RSP distribution of the HeCT reconstructed simulated water phantom.

Experiment



- RSP distribution of the experimental HeCT.

- Mauscript in review by PMB

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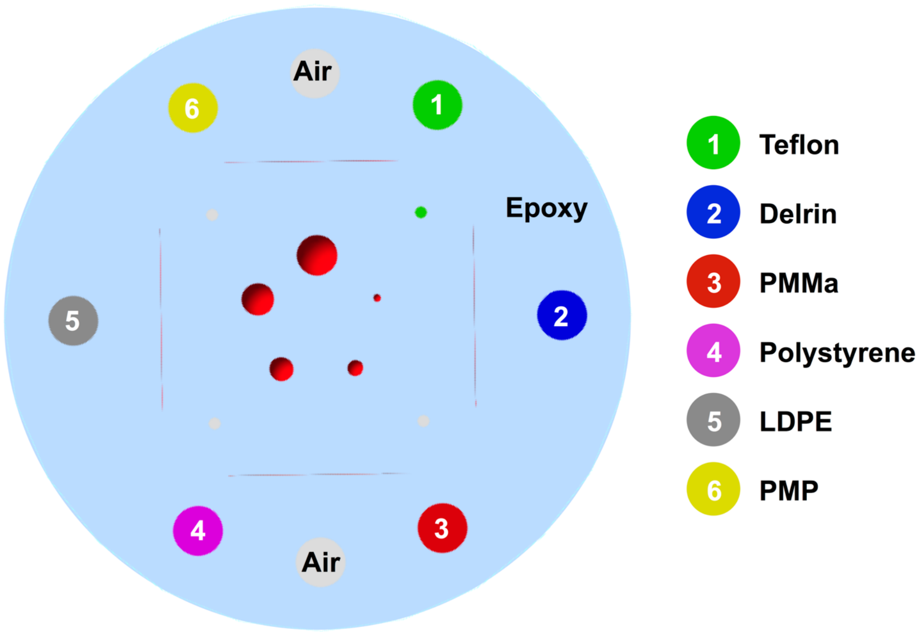
Relative stopping power accuracy



- Epoxy cylinder with different plastic material inserts
- RSP measured in a ROI of 3 mm radius in the center of the inserts and averaged over the 9 most central slices

- Catphan® CTP404 module.

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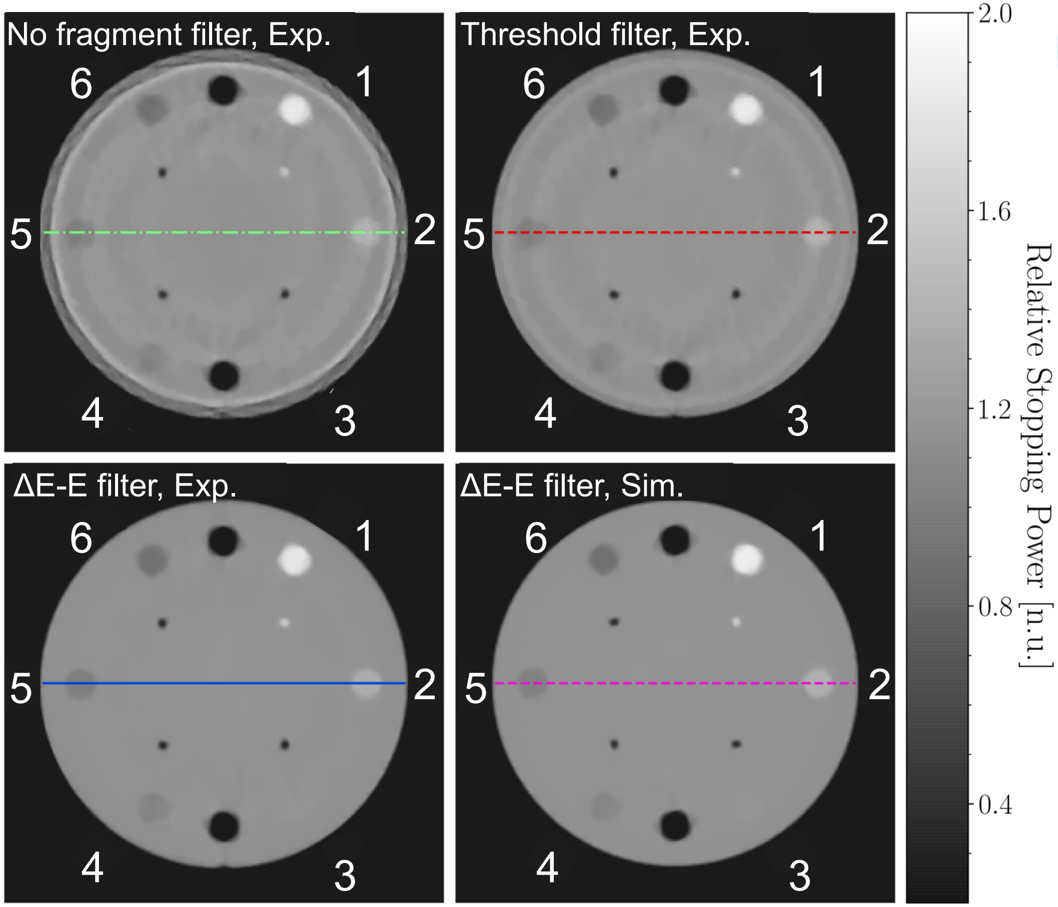
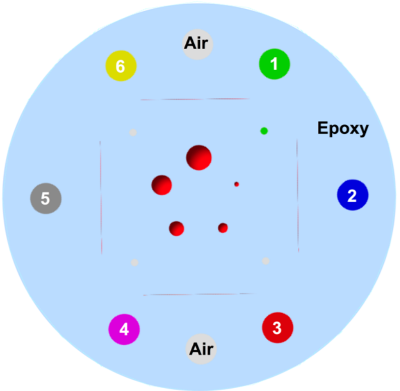
Relative stopping power accuracy





- HeCT reconstructed images of the Catphan® CTP404 with different filtering settings.

- Mauscript in review by PMB

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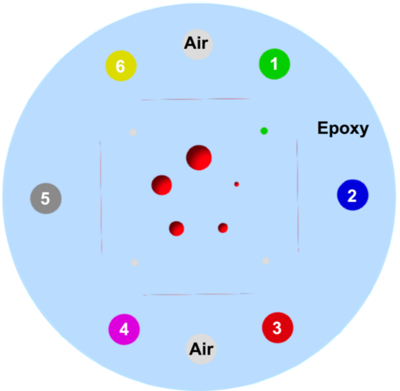
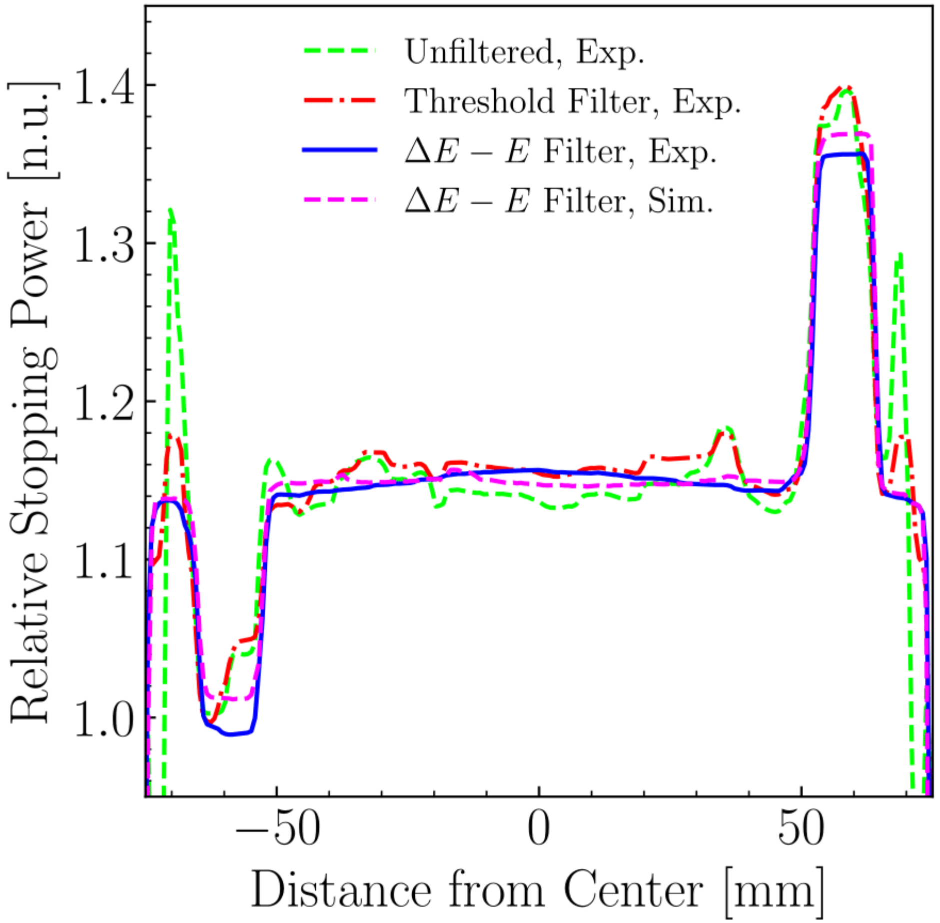
Relative stopping power accuracy





- Traverse profile through the HeCT reconstructed image of the CTP404 showing LDPE and delrin.

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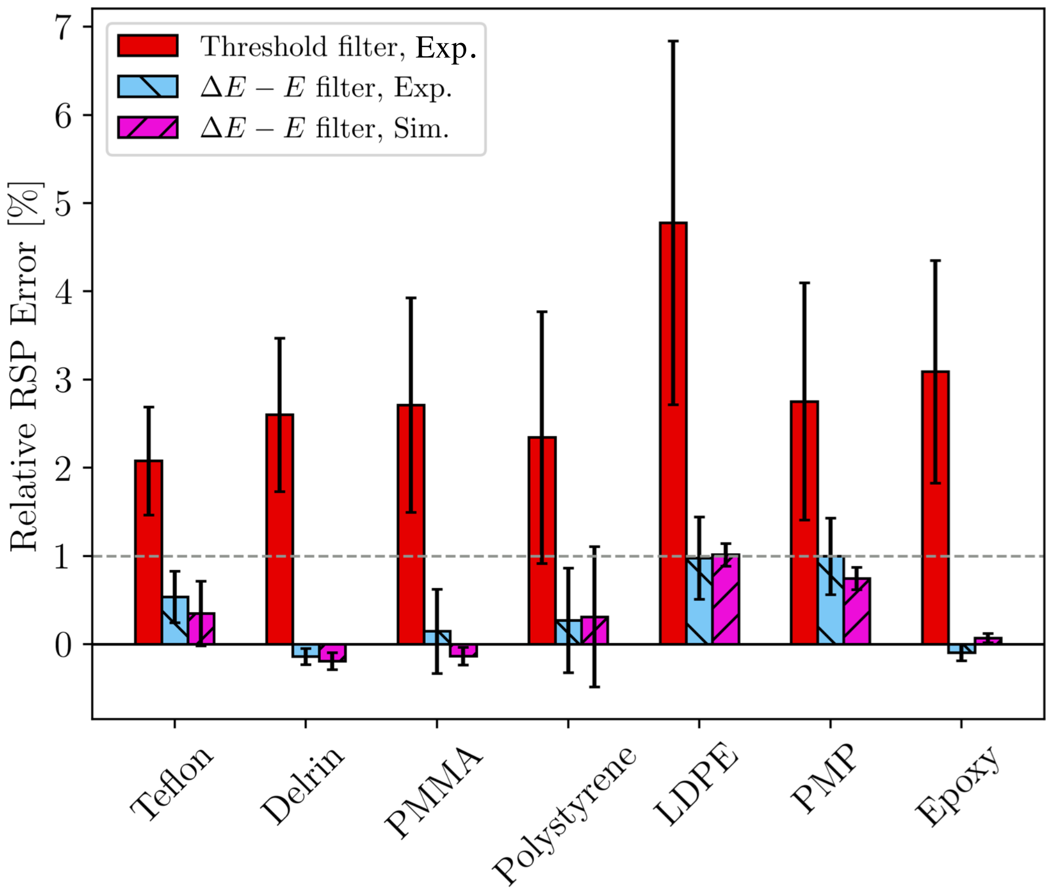
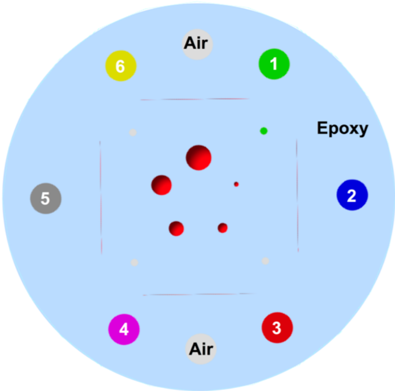
Relative stopping power accuracy





- Relative error of the RSP reconstructed for the CTP404 material inserts.

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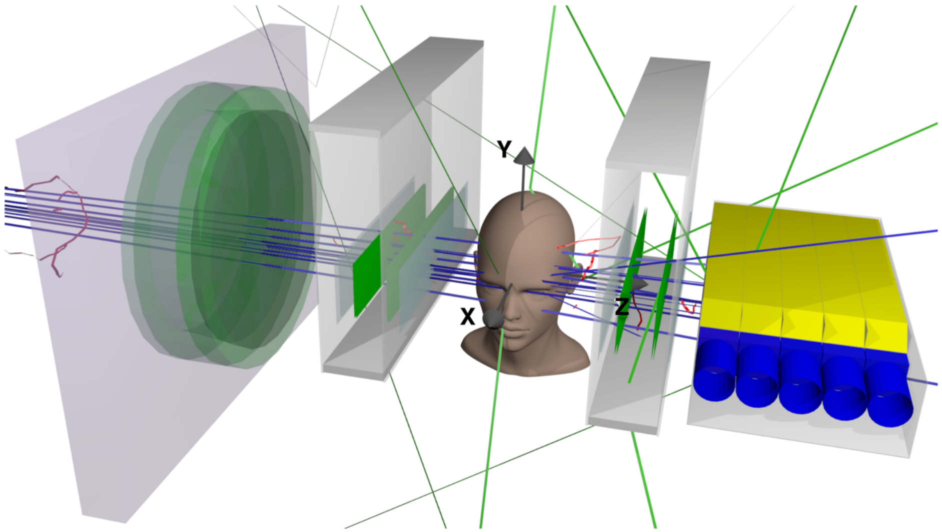
Application
pCT



- Piersimoni *et al.* (2017)

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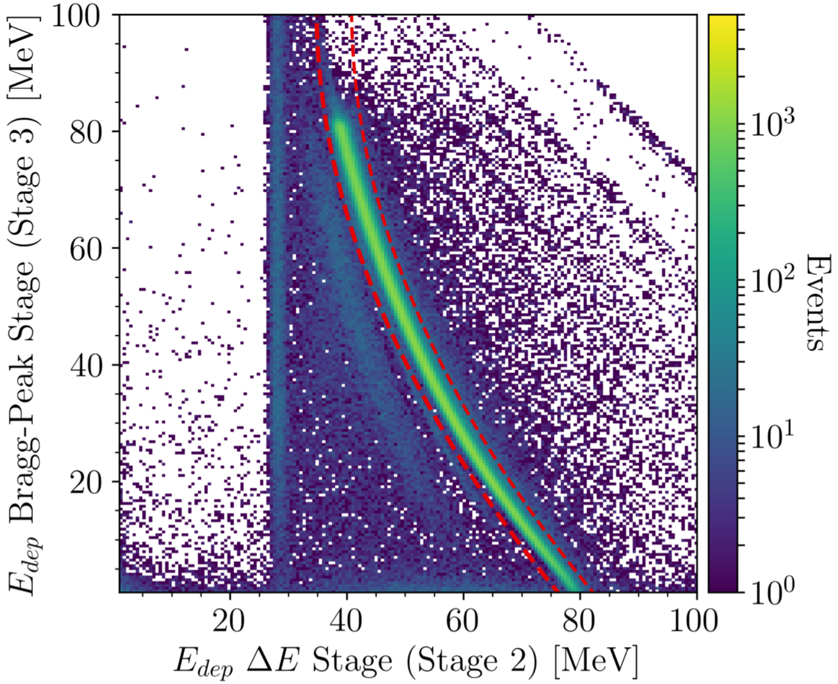
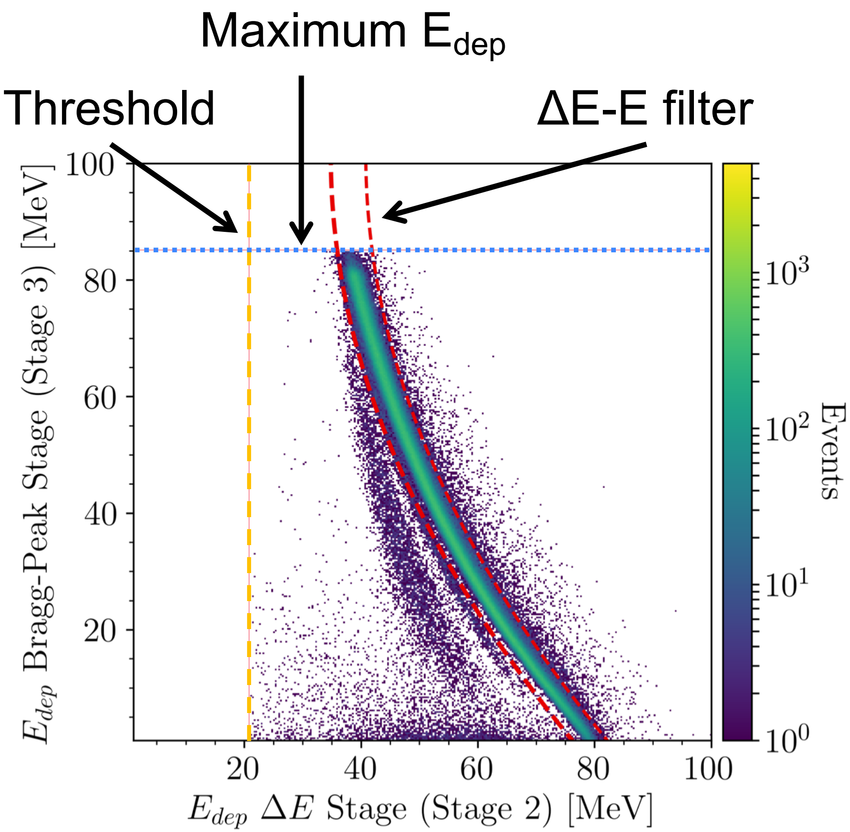
ΔE-E spectrum for pCT: Preliminary simulation results





- ΔE-E spectrum for a simulated pCT of an ideal water cylinder.
- ΔE-E spectrum after the 3σ filter and standard cuts are applied.

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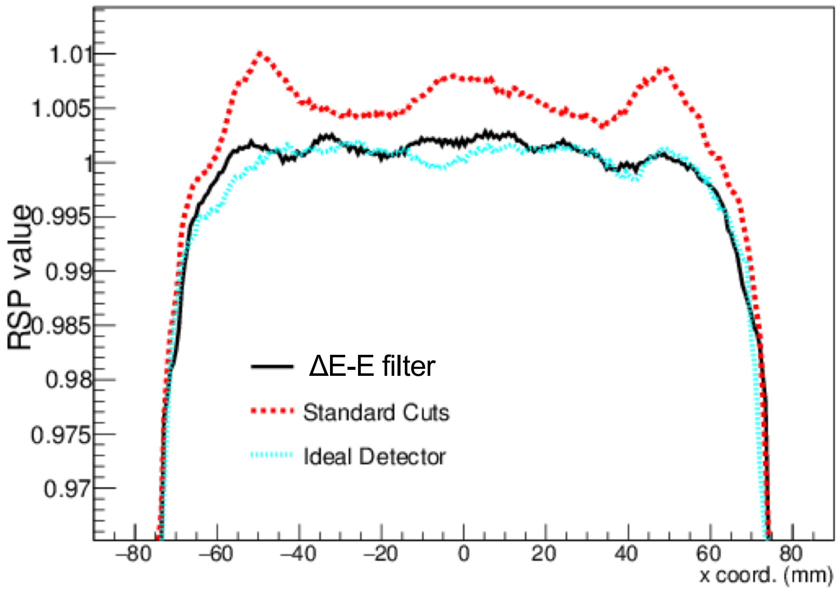
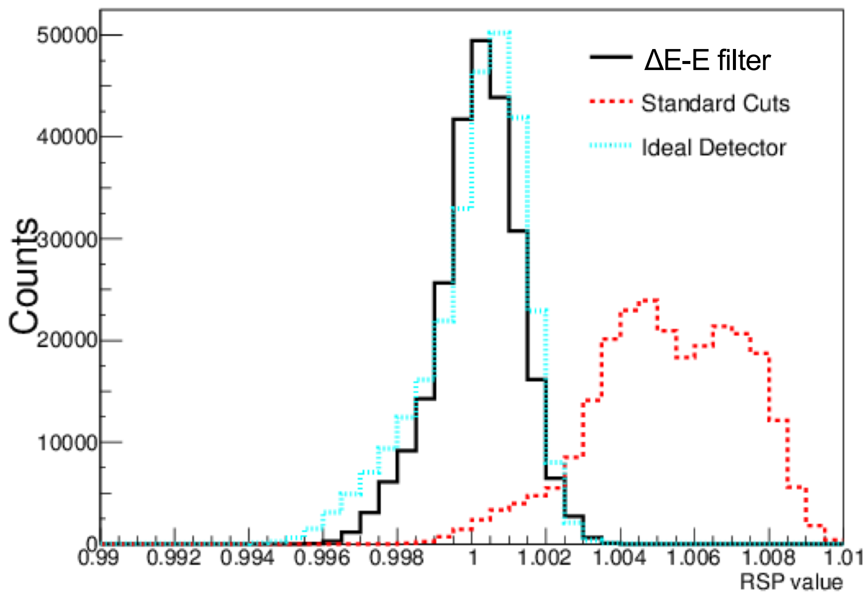
pCT of an ideal water cylinder: Preliminary simulation results





- Traverse profile through the pCT reconstructed image of an ideal water cylinder.
- RSP distribution in the center of the pCT reconstructed ideal water cylinder.

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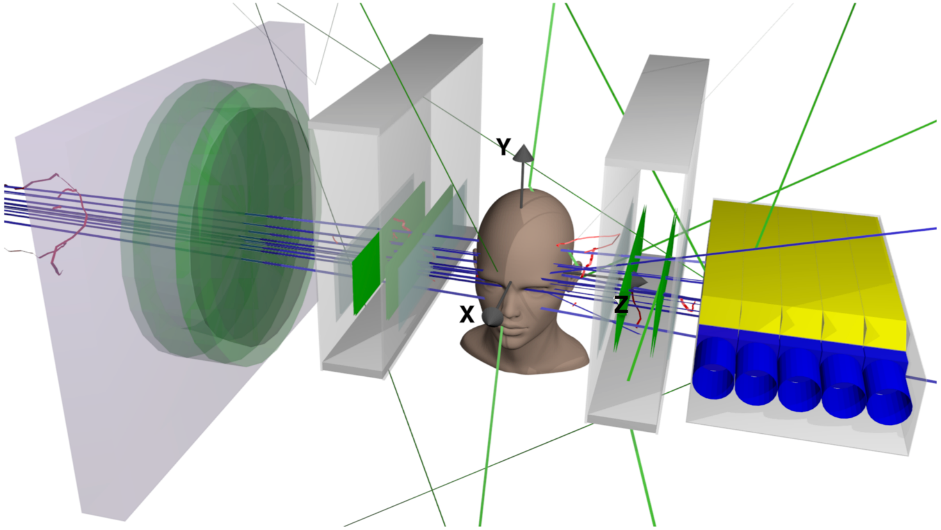
Conclusion



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Take home message

- Fragmentation processes were shown to cause sytematic uncertainties to HeCT visible as ring artifacts and low RSP accuracy
- The devloped ΔE-E filter effectively removes nuclear interaction noise/fragments and the correlated systematic errors
- The ΔE-E filter is applicable for all energy measuring detectors with longitudinal segmentation
- The filter works also for different ion types
  → HeCT and pCT ✓
  → Carbon CT (investigated...)

→ **With the ΔE-E filter accurate HeCT (and pCT) is possible**

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